Extending Cognitive Work Analysis and Engaging Nanotechnology: Embodied, Embedded and Socially Situated Processes

by

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

A modified version of Chapter 4 of this thesis has appeared in published form as,

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All the research, writing, and compilation of this paper has been conducted by Vivek Kant. Catherine M. Burns provided supervisory comments and monitored the growth of ideas and development of the paper.

Abstract

With current advances in material science and the growth of novel technologies, the nature of human technology interaction is changing. Specifically, the growth and convergence of Nano-, Bio-, Info- and Cognitive Science (NBIC) related technologies has resulted in the emergence of new systems, which requires considerations of the embodied, embedded and socially situated aspects of the human behavior for advanced interaction with intelligent and responsive environments. Currently, Cognitive Work Analysis (CWA) and the associated Ecological Interface Design (EID) are well positioned to draw requirements from these future smart environments; however, the role of the body in human knowing and acting as currently conceptualized in CWA requires further development. This thesis extends CWA by addressing the role of the body in human knowing and acting. Further, it also extends CWA by making the link between interpretive social approaches to human knowing and acting (specifically, symbolic interactionism) and CWA. Thus, this thesis supports the conception of the human in advanced technological environments as an embodied, embedded and socially situated construct.

In this thesis, CWA was extended at a fundamental level. This strategy required returning to the basic assumptions of CWA derived from Rasmussen's approach. A considerable portion of this thesis scrutinizes the fundamental assumptions of CWA by revisiting Rasmussen's papers and highlighting the engineering dimension of his approach. CWA is then extended via consideration of Rasmussen's approach along with other theoretical approaches from ecological psychology, action theory and symbolic interactionism, in order to produce a framework for gathering requirements for interface design. In this extended CWA, the first step allows for an interpretative understanding of the user's traditional ways of knowing and acting. Whereas the second step consists of an analysis amenable for eliciting the design requirements.

To show the applicability of the new extended framework, the work domain of nanotechnology is chosen. A field study was conducted in the area of nanotechnology that comprised of three subdomains pertaining to devices, robotics and materials. The requirements derived from these three areas were compared between the standard CWA and the extended CWA. In all the three cases the extended CWA supported the traditional CWA, as well as provided a greater number of requirements pertaining to the role of the body and the social dimension of activity in human knowing and acting. Therefore, this shows that the theoretical extensions have a practical feasibility in terms of using the extended CWA.

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Dedication

For my family, who have supported my intellectual vagrancy.

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List of Acronyms

Acronym	**Expansion**
ACM CHI	Association of Computer Machinery for Computer Human Interaction
AH	Abstraction Hierarchy
ASTM	American society for testing and materials
ConTA	Control Task Analysis
CWA	Cognitive Work Analysis
EID	Ecological Interface Design
HCI	Human Computer Interaction
HFE	Human Factors and Ergonomics
HFES	Human Factors and Ergonomics Society
HTA	Hierarchical Task Analysis
ICRA	International Conference on Robotics and Automation
ICTs	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
KETs	Key Enabling Technologies
LOC	Lab-on-a-chip
NBIC	Nano-, Bio-, Info-, Cognitive Science
NIOSH	National Institute for Occupational Safety and Health
NRC	National Research Council
NSF	National Science Foundation
POC	Point-of-care
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment
SocOrgA	Social Organizational Analysis
SRK	Skills. Rules and Knowledge

StrA	Strategies Analysis
UWNRG	University of Waterloo Nanotechnology Robotics Group
WCA	Worker Competency Analysis
WDA	Work Domain Analysis
WIDF	Waterloo Interface Design Framework

Chapter 1: Introduction

1.1 Purpose

1.1.1 Contribution 1

The main purpose of this thesis is to present a novel, systemic and systematic engineering framework for gathering requirements for advanced human-technology interface design: Waterloo Interface Design Framework (WIDF). WIDF extends the existing framework, Cognitive Work Analysis (CWA, Vicente, 1999), and makes it amenable for extracting requirements based on the embodied, embedded and socially situated dimensions of human knowing and acting.

Due to the influx and convergence of Nano-, Bio-, Info- and Cognitive Science (NBIC) related technologies, there is reduction in the size of technology and growth of “smart” everyday work environments. As a result, interaction of workers with these “smart” environments is expected to be more naturalistic involving both the mental and the physical. Therefore, for a requirements gathering framework for interface design in modern day work situations, there is the need for addressing human knowing and acting in terms of concepts of embodiment, embeddedness and social situatedness. Currently, CWA (also associated EID) is well-positioned to draw requirements from these future smart environments; however, the role of the body in human knowing and acting as currently conceptualized in CWA requires further development. WIDF extends CWA by addressing the role of the body in human knowing and acting (i.e., by treating the physical as intertwined with the mental). More specifically, CWA is extended based on the premise that the mind and the body are intricately linked and perception and action are dual aspects of the same phenomena. Perceiving is acting; knowledge is activity. Further, knowing and acting are socially situated phenomena. Thus, WIDF also extends CWA by making the link between interpretive social approaches to human knowing and acting (specifically, symbolic interactionism) and CWA. In other words, WIDF conceives of the human as an embedded, embodied and socially situated construct.

This thesis extends CWA by revisiting fundamental constructs; specifically, Rasmussen’s abstraction hierarchy (AH). Traditionally, CWA has addressed modern day engineered work systems. However, the AH in CWA does not make the concepts of “reasons for correct functioning” and “causes for malfunction” explicit in its structure. Due to the lack of visibility of these concepts, the linkage of CWA to the engineered dimension of systems is currently subdued. To make the linkage explicit, it becomes necessary to revisit the AH from Rasmussen’s original framework and consider the notions of reasons and causes in detail. In Rasmussen’s framework, the notions of reasons and causes have been developed from the viewpoint of an engineering approach to systems design. CWA derives from Rasmussen’s approach (Rasmussen, 1986, Rasmussen, Pejtersen & Goodstein, 1994) and also inherits these concepts. However, currently, they are not explicitly visible. In other words, the engineering viewpoint from Rasmussen’s original approach has not surfaced visibly in the structure of CWA. Making the notions of reasons and causes explicit allows for providing an extension to CWA. Highlighting the engineering dimension that lies at the basis of the original approach (for e.g., Vicente & Rasmussen, 1990), also allows for a considering concepts of correct functioning and malfunction explicitly. Thus, making it possible to easily develop CWA in relation to other areas of HFE, such as safety engineering. Further, accounting for reasons and causes for structuring the AH provides the possibilities for further extensions that support the original ideas from Rasmussen and Vicente, as well as provides for extending CWA with other approaches such as symbolic interactionism and action theory, as done in this thesis. To summarize, revisiting fundamental concepts will allow for highlighting the link between the engineered dimension of systems and CWA; thus, providing considerations for the treatment of human interaction with engineered “smart” work environments in an enhanced manner.

1.1.2 Contribution 2

To demonstrate the requirements-gathering capacity of the extended CWA framework, this thesis provides an empirical foray in nanotechnology. Even though Human Factors/Ergonomics (HFE) visionaries have promulgated the intersection of nanotechnology and ergonomics (Karwowski, 2006; Szewczyk, 2014), there is still a lack of empirical studies in this domain. The empirical observations and ethnographic study presented in this thesis provides an opportunity for demonstrating an intersection of nanotechnology and HFE. In particular, the second contribution of the thesis is to explore the relevance of traditional CWA and extended CWA (WIDF) to this new domain. To date, to the best of my knowledge, no empirical studies have been conducted in CWA using nanotechnology as a research area. Addressing nanotechnology allows for the exploration of CWA in a new domain; in particular, a domain with distinctly different physical work characteristics than the previous domains where CWA has been used.

The research study on nanotechnology, under the rubric of this thesis, has been conducted at university research laboratories. Research in university nanotechnology laboratories, i.e. treating the laboratories as work domain, is needed for two main reasons. First, there is a necessity for understanding the varied scientific and technological practices in the laboratories so as to aid knowledge work. Second, the growth of new modes of research is rapidly changing the research landscape and the university research laboratories are crucial actors in the innovation system (Ghafele, 2012; also, Veugelers & Del Rey, 2014, for Europe; Hughes, 2006, Hughes & Kitson, 2012 for UK; National Research Council, 2012, for USA). For example in the USA, based on the data gathered from nanotechnology activities, university laboratories, among other actors, continue to have a marked impact on the research outcomes (Nanomap, 2015).

Typically, the major focus of ergonomics in research labs has been in terms of recommendations for safety and procedures for optimal work in the laboratory facilities (e.g. Kerst, 2001, OSHA, 2011). Apart from the ergonomics of laboratories, scholars in a multitude of areas, such as philosophy of science (e.g., Baird, 2004), science and technology studies (e.g., Sismondo, 2009, Ch. 9 for an overview), among others, recognize the material nature of knowledge practices in scientific and technological laboratories. Material knowledge practices are prominent in a research area such as nanotechnology. Researchers rely on microscopes and visualization software for studying entities of the small scale. Specifically, designing *for*, as well as, *with* nanotechnology, requires a careful and deep understanding of the intervening technologies and mental models of researchers. In other words, there is a requirement for augmenting creative knowledge work in laboratories with proper tools — hardware and software (for e.g., see Tory and Moller, 2004, for human factors and scientific visualization; Gould, 1995, for HFE aiding in intellectual work). The design of such tools requires a contextual study of laboratory research work; thus, enabling an insight into the mental models of the researchers. In turn, this allows for the design of frameworks and tools for HFE to enable creative and analytic discoveries in nanotechnology.

1.2 Motivation

1.2.1 Challenge of Future Technologies for Human-Technology Interaction

CWA is extended with a view towards the future of technology and work. The concept of work is rapidly changing due to the influx and convergence of new technologies (Hollnagel, 2014). Prominent among these are the consortium of the "NBIC" technologies — Nanotechnology, Biotechnology, Information technology and technologies related to Cognitive Science (Roco & Bainbridge, 2003; Roco, Bainbridge, Tonn & Whitesides, 2013). Sponsored by the National Science Foundation (NSF), USA, Roco and Bainbridge's 2003 report anticipated important changes in society in the coming 20 years due to the impact of the convergence of NBIC technologies (Roco & Bainbridge, 2003; also see the study stressing the relation to society in Roco, Bainbridge, Tonn & Whitesides, 2013). Cognizant of the upcoming changes and rapid technological convergence, governments around the world are adopting cutting-edge technologies for seamless integration for the future. The European Commission has stressed on the convergence of many technologies for the future such as Geo-, Micro-, and Nano-, among others (Nordmann, 2004). Similarly, the Canadian Government's National Research Council (NRC) has made innovation in the field of science and technology a federal priority to ensure the success of Canada's strategic plan for strong economic growth, healthy Canadians, clean and healthy environment and access to innovative and knowledge based economy (CNRC, 2013-14). Among the areas to be addressed by this research plan includes Information and Communication Technologies (ICTs) and emerging technologies such as nanotechnology, molecular sciences, and semiconductor technologies, among others. In short, there is a growing recognition about the increasing convergence and rapid changes in technologies of the future.

Due to the improvements in material science and nanotechnology, the technological convergence is expected to reduce the size of information devices. As a result, the demands on human technology interaction and everyday work in HFE will increase. Recently, in the field of HFE, Hollnagel (2014) mentions that the nature of work in the 2010s is radically different from the time when HFE was originally formulated. He recommends that HFE as a field should address these changes in order to grow as a discipline. The change in the nature of work implies that in the field of human technology interaction these novel technologies will have a direct impact (Lundstorm & Wong, 2013). Since information devices will decrease in size and will be seamlessly merged with the environment, the nature of interaction is expected to become more embodied, embedded and socially situated. As a result, there will be a requirement for changes in the manner in which systems must be designed. In order to address these changes there is a need for analytical tools and frameworks for addressing and comprehending the changing nature of human work in a multitude of technological domains and settings.

1.2.2 HFE and Nanotechnology—new challenges

In terms of novel technologies, nanotechnology has emerged as prominent. Nanotechnology, while already impacting society, is expected to become a key technology in the future. The Canadian government's report (CITC, 2011) addressing "Canada's Evolving Nanotechnology Industry and Future Implications for the ICT Labour Force" indicates that provinces have started working towards incorporating newer technologies to promote economic activity. For example, the province of Alberta has adopted a strategy and goal for the year 2020: "By 2020, Alberta will achieve a two per cent share of the global nanotechnology market – generating an estimated $20 billion of new economic activity" (CITC, 2011, p.4). On the other side of the Atlantic, the European Commission's (2011) report on Key Enabling Technologies (KETs) also identified growing technologies such as nanotechnology, industrial biotechnology, and advanced materials, among others. Not surprisingly the European Commission has launched an active strategy for the economy, based on KETs (European Commission, 2012). These key-enabling technologies will bring about rapid changes in the nature and content of work; further, these technologies are considered strategic to the growth and well being of society (c.f. Foladori & Invernizzi, 2005).

Nanotechnology research has provided impetus to the development of a large array of materials and devices. These products of nanotechnology are rapidly being employed in a variety of domains, ranging from manufacturing to healthcare (CPI, 2014; Roco et al., 2013). HFE visionaries have also emphasized the role of nanotechnology for the future of society (Karwowski, 2006; Szewczyk, 2014). Currently, the emphasis of HFE research related to nanotechnology has been largely focused on health (Greaves-Holmes, 2012; NIOSH, 2014; WHO, 2013), possible use of nanomaterials for design ergonomics (Chowdhury, Sanjog, Reddy & Karmakar, 2012), developing countries (Rizvi, Khan & Ishrat, 2009), and sustainability (Yang & Miao, 2010). This thesis extends nanotechnology studies in empirical domains related to devices, robotics and materials. In general, the physical and chemical processes required at the small-scale (both micro- and nano-) is different from the meso- and macroscale; thus, posing design challenges for HFE not encountered before at larger spatial scales. Hence, in order to successfully design for nanotechnology, it will be necessary to link the nanoscale entities with their usage at the human scale. In short, devising small-scale technologies as well as later using them, presents novel research challenges for HFE.

1.3 Theme and Scope of the Thesis

1.3.1 Theme: Embodied, Embedded and Socially Situated view of human interaction with technology

In designing for people involved in their everyday activity, the design engineer has to understand the conduct of people involved in their work activity via an interpretive approach. This focus on human conduct in situations eschews a division based on mental and physical; social and biological; and knowledge and activity; among other widespread dualisms. In fact, work involves the body as much as the mind and the behavior of the individuals are best understood in terms of a social endeavor. In short, there is a necessity for holistic understanding of the work. With technological leaps in material science, information-processing devices are decreasing in size — they are not only becoming ubiquitous but are embedded in work environments. These technological devices become “invisible” to the people involved in these “smart” environments. Thus, this requires a holistic embodied mode of interaction for systems that considers people as embedded in their work environments. Therefore, the designer should treat the notion of knowing and acting as intertwined meaningful constructs for human-technology interaction design that has to be understood from the point of view of the people involved (essentially, an interpretive approach).

A characteristic feature of modern day work is the multitude of social roles and perspectives — ranging from individual users and designers to institutions and governmental regulatory bodies — constantly shaping everyday activities. Work in modern technological environments is best characterized as a multitude of dynamic processes where some changes are quite fast whereas many occur slowly over decades. These ongoing processes keep the entire work system in the state of dynamic stability. Coupled with dynamic stability, work systems are complex and emergent. Actors in everyday work environments *adapt* to the work, *adopt* technologies for their work and also *appropriate* technologies for their own purposes. This tension between the notions of adaptation, adoption and appropriation, among others, plays a central role in the emergence of new roles and opportunities, as well as large-scale work related changes in society. Thus to understand modern day work systems, it is necessary to address the embodied, embedded and socially situated aspects of everyday work in technological environments.

1.3.2 Scope: Extending CWA

The particular scope of the framework proposed in this thesis derives from its overarching theme. In this thesis, CWA is extended to derive requirements for human technology interaction in everyday work systems. The extension of CWA (WIDF) is constructed based on the premise that design of interaction is a *relational* and *systemic* concept. Typically, interaction via interfaces is treated as attributes of the technology. In contrast, a different manner of addressing interaction (and hence, interfaces) is in terms of relational concepts; i.e., the interface is a relation linking the human and the technology. On the side of the human, the interface appears as the conduit that allows the machine to be controlled, operated or used. Since technologies allow certain practices while curtailing others, in terms of interfaces, it means that the human, who is creative and flexible, is constrained in a particular manner due to the underlying technology and mode of interaction. In contrast, on the side of technology, the interface acts as a conduit for receiving input from and providing output to the human, based on its technical capabilities. The relation between the human and technology can be best envisioned by an analogy of a glass jar containing oil and water. The interface between the oil and the water is simultaneously a part of both oil as well as water—it is a relational concept. Similarly, the interface between human and technology is a relation and hence a part of both the human and technology. It cannot be envisioned separate from both or simply reduced to one. For successful human technology interaction via interface design, both the human and technology must be accounted together as a unified entity.

Along with being relational, interfaces are envisioned as systemic concepts. Interfaces are defined not only by the human and the technology but also the entire system of which it is part. In terms of the above analogy of oil and water, the interface is shaped by the property of not only the two fluids but also the whole bottle. This implies that interfaces are shaped by a variety of contextual factors that may be non-obvious or invisible to the people operating or using the technology. For example, the design of military aircraft cockpits has been a core aspect of human factors since World War (WW) II. However, the ethnographer Weber (1997) notes that typical military aircrafts cockpits embody a male bias in their ergonomic considerations. Aircraft cockpit designs are based on the engineering specifications for male anthropometric measurements. Moreover, the decision to alter the cockpit for females results in design considerations not only at the anthropometric levels but also at the technical level of the aircraft, institutional levels of Pentagon, and the wider business community of aircraft manufacturers. Weber highlights the various marketing forces, political considerations, legislative processes and lobbying in the government, along with the technical considerations that brought about the design of the military aircraft cockpits as “women-friendly”. Therefore, the cockpit that interfaces between the human and the aircraft is not only dependent on technical factors but is embedded into a medley of considerations that are often non-obvious. As this example illustrates, human-technology interface design should be treated as a systemic concept based on the overarching system.

WIDF derives from four major strands of thought, the engineering approach of Jens Rasmussen and Kim Vicente, the ecological psychology of James J. Gibson, the symbolic interactionism of Herbert Blumer, and the motor control and action theory of Nikolai A. Bernstein. All these strands are brought together to form a coherent engineering framework for gathering requirements for human technology interaction in complex work systems. Since the framework is devised for advanced human-technology interaction design, it takes into account the safe, acceptable and correct functioning of systems.

The thesis focuses on extracting design requirements at the level of individuals. Modern day work systems are affected by many factors at multiple levels ranging from individuals roles, teams, organizations and institutions, among others. Due to the scope of the thesis, teams, organizations and the like are not explicitly addressed, apart from their contribution to the work context. Further, the scope of the thesis is limited to eliciting the design requirements for interfaces rather than other related applications in HFE, such as training.

1.4 Structure of the thesis

The thesis consists of 11 chapters. The current Chapter 1 serves as the introduction. Next, Chapter 2 consists of a description of the past research on CWA and situates it in the major themes underlying human technology interaction in both HFE and HCI. Chapter 3 presents the extension of CWA. Chapters 4-9 presents a demonstration of the proposed framework in the field of nanotechnology. Further, in order to show the applicability of WIDF, the design requirements of WIDF are compared to the ones obtained by CWA. Specifically, chapter 4 presents the ethnographic study of devices and the next chapter 5 presents the engineering analysis for the same. Similarly, chapters 6 and 7 present the details of robotics; whereas, chapters 8 and 9 present the ethnographic study and models for materials. The thesis concludes with putting nanotechnology in perspective (chapter 10) and discussing limitations and directions for future research (chapter 11).

Chapter 2: CWA and its extensions

2.1 Introduction

The aim of this chapter is to present a survey of research related to CWA. It also situates CWA in terms of major themes present in human technology interaction research in both HFE and HCI. Thus, it allows for the identification of aspects that could be used to extend CWA to provide a more detailed understanding of human knowing and acting in given work contexts. This chapter identifies the important aspects related to human technology interaction that will be used as a basis for extending CWA in the next chapter.

2.2 CWA and its extensions

Even though CWA has a broader history before 1999, the book *Cognitive Work Analysis* (Vicente, 1999) can serve as a useful starting point as it provides a unified methodological statement. Vicente's (1999) book *Cognitive Work Analysis: Towards Safe, Productive and Healthy Computer based Work* is a conceptual and systematic account of the CWA approach. engineering. CWA is a constraint-based framework for analyzing work and designing for human adaptation in work contexts. Specifically, it derives from the approach developed by Jens Rasmussen and his colleagues at Risø Laboratories, Denmark, and ecological psychology of J.J.Gibson. CWA consists of five main steps ranging from Work Domain Analysis (WDA) to Worker Competency Analysis (WCA). These steps begin from the environment and progressively move towards the person. Therefore, the WDA consists of a description of the environment in terms of a conceptual tool, the abstraction hierarchy (AH). Next, the cognitive tasks conducted on this work domain is addressed in terms of another conceptual tool, the Control Task Analysis (CTA). The third step, the Strategies analysis (StrA) accounts for the various strategies that are involved in the tasks. Next, interpersonal cooperation and organizational interactions are addressed in Social and Organizational analysis (SocOA). Finally, the skills, rules and knowledge required for the workers to operate in the work domain is addressed by the Worker Competency Analysis (WCA). In these five steps, the primary idea is to model the constraints that set the boundaries for safe and acceptable work in the given domain.

Since 1999, CWA has been extended theoretically as well as empirically. In a review of CWA design applications Read, Salmon and Lenné (2012), highlighted that the majority of CWA applications have been associated with interface design. Other applications include functional allocation; job/team design; workplace design; among others. In terms of interface design, CWA's (and associated EID's) impact has been steadily felt in both the causal and intentional domains.

In terms of the causal domain, example application domains include, but are not limited to, network management (Burns, Kuo & Ng, 2003); manufacturing (Horiguchi, Burns, Nakanishi, & Sawaragi, 2013); and milk pasteurization (Reising & Sanderson, 2002a, 2002b), among others. In contrast to causal domains, CWA has also been applied to intentional domains (Hajdukiewicz, Burns, Vicenete, & Eggleston, 1999); such as, naval command and control (Burns, Bryant, Chalmers, 2005), social engagement and networks (Euerby & Burns, 2012, 2014), and simulated environments for military training (Jenkins, Stanton, Salmon & Walker, 2011), among others (see Read et al, 2012, for a broader list of applications; Read, Salmon & Lenné, 2014, for a short discussion of current practice and future practitioner requirements; Jiancaro, Jamieson & Mihailidis, 2014, for review of CWA in healthcare; Bisantz & Roth, 2007 for a review of cognitive task and work analysis; also, Bisantz & Burns, 2008; Roth & Bisantz, 2013 for a comprehensive overview; as well as Lintern, 2008, 2009 for a theoretical background). Since the aforementioned review papers have discussed both theoretical and methodological changes in the broad landscape of post-1999 research in CWA, the following addresses a conceptual sampling of these novel additions.

Post-1999, CWA has had important extensions in terms of theory and empirical research. In terms of a theoretical basis, CWA has been linked to sociotechnical systems theory from the Tavistock Institute (Read, Salmon, Lenné & Stanton, 2014). Read and colleagues emphasize that sociotechnical systems theory and CWA have complementary perspectives. Further, the authors provide HFE attributes which could be used to extend the CWA approach for systems design in terms of a CWA-STS toolkit. This toolkit can be viewed in light of the previous research conducted by Stanton and colleagues (for e.g., Stanton & Bessell, 2014; Mcllroy & Stanton, 2011; among others). For example, Stanton and Bessell (2014) have used CWA to understand the rich interactions occurring in the control room of a submarine. Using data gathered from observations and interviews, the five phases of the CWA analysis were conducted. The authors note that the activity involving the returning of the periscope to a proper depth consists of sociotechnical interdependencies involving people, technologies, as well as rules for joint cooperation for the activity at hand. Sociotechnical flexibility in relation to CWA has also been addressed by Jenkins and colleagues (Jenkins, Stanton, Walker, Salmon, & Young, 2009). Using a domain of the device "Apple iPod", the study uses the first three phases of CWA along with the contextual activity template to increase the flexibility of the system. In other words, the functions extracted using the abstraction hierarchy in the first phase are used along with the contextual activity template in cases where functions are not enough for providing clarity. Thus, this provides a link between analysis and design in order to show how the flexibility of the system can be achieved for greater adaptability.

Along with the sociotechnical dimensions of systems, CWA has also been extended to account for individual phases and additional tools that could be used along with CWA (e.g. see Jenkins et al., 2007 for development of a CWA tool). For example, in a series of papers (for e.g. Naikar, 2006; Naikar, Moylan & Pearce, 2006; among others), activity analysis in complex systems has been addressed using CWA. A contextual activity template is based on the notion that in some work systems both functions (problems to solve) and situations (recurring) are required (Naikar, Moylan & Pearce, 2006, p.377). Further, the contextual activity template also provides an insight into the various combinations of work situations and functions that are possible in the domain. The various combinations can be used to identify the different cognitive demand on the workers. Along with the contextual activity template, there is a growing stress on the further applications of CWA beyond its traditional use in interface design (Naikar, 2006), such as, for training needs and training system requirements (e.g. Naikar & Sanderson, 1999; Naikar, Pearce, Drumm & Sanderson, 2003). Training needs and strategies also need to be developed for managing human error. The emphasis of using the training approach, based on CWA, is to develop technical skills to understand the relevant boundaries and scope of possibilities (Naikar, 2006; Naikar & Saunders, 2003). Therefore, training the participants allows for providing insights into boundaries of acceptable behaviors and in effect the removal of errors.

Along with training and errors, CWA has also been extended in terms of identifying human factors hazards by integrating other hazard identification methodologies (for e.g., Hassall, Sanderson & Cameron, 2010; also Wu, Zhang, Liang & Hu, 2012, for CWA and risk for oil and gas processes). In these approaches, the new processes and models are developed with CWA as a basis. For example, HumHID (Hassall, Sanderson & Cameron, 2010) presents analytical steps for systems selection and decomposition and using it with hazard analysis techniques. Preliminary results have been demonstrated using desktop simulations for chemical processes.

Another area in which CWA can be used is to evaluate system design proposals for developing new systems (Naikar & Sanderson, 1999). By listing the needs and requirements at each level of the AH, the basis of the new system can be devised. A fourth novel area of application of CWA is team design. Using examples from military domains, Naikar (2006; also Naikar, Pearce, Drumm & Sanderson, 2003) demonstrates the applicability of contextual template analysis and the control task analysis for team design (also see Mcllroy & Stanton, 2011, for use with CWA). Team design has also been addressed by other approaches extending CWA. For example, in regard to teamwork, CWA was extended for teams by the uses of decision wheels (Ashoori, 2012; Ashoori & Burns, 2013). In this line of thought, multiple decision ladders were used to account for the whole team. The interaction between various teams was analyzed and modeled for two fieldwork sites relating to a birthing unit (Ashoori, Burns, d'Entremont & Momtahan, 2014; also Burns, 2014, for a reinterpretation) and a software development team (Ashoori, 2012). Team CWA is portrayed as a supplement to the traditional CWA and allows for the facilitation of information and identification of constraints related to teamwork settings. Thus, another manner of understanding team cognitive work analysis is to view it as part of the social organizational phase of CWA (Burns, 2014).

In post-1999 research pertaining to CWA, the first two phases of work domain analysis have been developed in great detail by researchers (Naikar, 2011). More recently, the other phases pertaining to strategies analysis, social organizational analysis and worker competency analysis are also being developed. Strategies analysis has been addressed by researchers such as Naikar (2006); Hilliard, Thompson, and Ngo (2008); Burns, Enomoto, & Momhatan (2008); Roth (2009); Cornelissen, Salmon, Jenkins, and Lenné (2013); and more recently, Hassall and

Sanderson (2012). Cornelissen et al (2012) presented a structured approach to strategies analysis. Using iPod as a case study, the authors introduce the strategy analysis diagram. The new aspect of the strategy analysis diagram is the fact that it adds the possibility of choice between various strategies and a formal structure for identifying the flow of strategies in terms of various levels of the diagram. Therefore, using the strategies analysis diagram, it would be possible to identify the flow of strategies through various levels by following the nodal structure of the identified nodes at each level (Cornelissen et al, 2012, p. 558, fig. 9).

Along with Cornelissen et al (2012), Hassall and Sanderson (2012) present a formative approach for strategies analysis. Currently, the use of strategies is typically domain specific. Therefore, to understand strategies from a generalized perspective, the authors present a two-phase approach. The first phase consists of a generic preparation phase in which the main aim is to identify generic constraints that allow for the possible range of strategy selection. Strategies can be based on factors related to the situation and task on one hand and factors relating to time pressure, difficulty of executing the task, and risk level, on the other. These factors can together be used to form a “constraints matrix” (Hassall & Sanderson, 2012, p. 229, table 3). Strategies appear in many forms such as “intuitive”; “cue-based”; “imitation”; among others. These strategies are generic in nature and sufficiently small in number so that they can be applied over a variety of domains. Since using a strategy can be a success or failure, there is a need for understanding the range of strategies and the selection that leads towards successful outcomes. Therefore, in the second phase of the proposed analysis, the impact of the strategies is evaluated in relation to the situations, tasks and workers. This second phase consists of four steps. In step one, the activity of interest is identified. Next, the strategy-selection criteria are operationalized. Third, the likely categories of strategies are identified. Finally, factors promoting strategy selection and change are identified. These four steps together help in determining how the strategies can be used to improve systems design. Along with strategies analysis, the social-organizational phase of CWA has also been a growing area of research (see Ashoori, 2012; also Ashoori and Burns, 2013; Burns, 2014).

The final phase of CWA consists of worker competency analysis. In terms of Worker Competency Analysis (WCA), Vicente (1999) had used Rasmussen’s SRK. However, this phase in general lacks well-defined tools (Kilgore & St-Cyr, 2006); as a result, the importance of this phase is undermined. A notable exception has been the SRK inventory presented by Kilgore and St-Cyr (2006). In this paper, the author introduced the use of skill-based, rule-based and knowledge-based behavior in an inventory format for linking the fifth phase of competency analysis to other phases for an enhanced integration (specifically, linked to the decision ladder). In a book chapter, Kilgore, St-Cyr and Jamieson (2009), present a pedagogical approach to the linkage between WCA as well as other phases was provided for the phases of CWA for air traffic control simulator TRACON (also see Jenkins, Walker, Walker & Salmon, 2008, for interconnections between different layers of CWA). In another development of the final phase of worker competency analysis, Mcllroy and Stanton (2011) provide an inventory with four entities: skill-based, rule-based, and knowledge-based behavior, along with the nodes taken from the object related process levels of the AH (for e.g., purpose-related functions). The main import of Mcllroy and Stanton's (2011) formulation is its emphasis on requirements specification. By this approach, the authors provide a consideration of the WCA in the earlier stages. Further, this new approach by Mcllroy and Stanton (2011) shows that both the AH and worker competency analysis can inform requirement specifications and can be included in requirement specification documents. The inclusion of AH and WCA can provide insights into constraints, visual analysis and functional relationships that are not addressed by the current text-based specifications.

Along with these developments in the core aspects of CWA, the work domain analysis of CWA has been used in novel terms of flexibilities of scale and modeling. For example, using the community of University-Community Partnership for Social Action Research (UCP-SARnet), Euerby and Burns (2014, also Euerby & Burns, 2012) conducted a longitudinal study on the design and evaluations of community systems. Communities are entities that are not so tightly connected as teams but the members share common goals. Supporting communities presents different challenges than the ones encountered for teams and groups. In an earlier study (Euerby & Burns, 2012) modeled the community based on insights from communities-of-practice approach and CWA. In this model, the domain community work and the community are presented together, albeit in different columns. At the lowest level, that of physical form, both of these share common relationships, projects, and events. Whereas at higher levels, they have different sets of purposes, values, and priority measures. The model was used to redesign the community website. In an extension of this research, the authors (Euerby & Burns, 2014) studied the degree of social connectedness and communication levels. Due to the redesign of the website, increased levels of communication as well as an increase in connection between people were observed. The use of sociological theories shows the possibilities for introducing human factors methods for community building.

Apart from modeling whole communities, a different level of scale is used to model the body in CWA. This approach towards understanding the body is specifically addressed in the area of CWA applications in healthcare. Even though the area of CWA and healthcare is too large for a summary here (see Jiancaro, Jamieson & Mihailidis, 2014, for a review), a few notable examples are highlighted to demonstrate the innovations in this area. For example, Hajdukiewicz and colleagues (Hajdukiewicz, Vicente, Doyle, Milgram, & Burns, 2001) modeled a medical environment that presented the model of the patient and the cardiovascular system, among other aspects, in terms of a work domain model. Miller (2004) provided a work domain analysis framework for modeling intensive care unit patients. In this approach, a recursive diagnostic framework, she presented Stafford Beer's viable systems model to represent the patient as a dissipative structure. Further, she used a recognition primed decision model to represent the information resources for supporting clinical decision-making. More recently, CWA has been used along with persuasive design to improve patient's understanding of their affliction and providing motivation for self-monitoring was used to model the blood pressure system at the patient level and the bodily subsystems level. Further, EID coupled with using persuasive design principles was used to facilitate the patients' appropriate goal-directed actions to successfully self-monitor their health (Rezai & Burns, 2014).

The above have been few notable directions in which CWA has been developed post-1999. CWA is an active area of research and it is expected to show further research and development of theoretical and methodological tools in the future. Further, a few notable insights are also prevalent which are pertinent to the direction taken by this thesis. The discussion of the body is present in the healthcare context; however, CWA and its proponents are silent about knowing and acting as a fundamentally embodied construct. Embodiment does not mean the presence or absence of the body, rather the body is an integral aspect of behavior and cognition, and cognition cannot be comprehended in the absence of the body. In other words, cognition is corporeal. This corporeal discussion of cognition and cognitive work is not prevalent in post-1999 research in CWA. Further, post-1999 CWA has shown an increase in addressing the social dimensions of systems. However, the notion of sociality is addressed in terms of teams and communities. The emphasis on the individual as a fundamentally social construct is not explicit. These three aspects can be viewed in light of the sociotechnical formulation that lies as the basis of CWA.

Finally, a few notable challenges remain for CWA in relation to theory, methodology and praxis (Naikar, 2011). These include challenges related to interface design (EID); team/organizational design; as well as aspects of CWA beyond the WDA. In terms of interface design (Naikar, 2011, p.13), the first challenge is to extend the empirical evaluation for a variety of systems. Second, in display design, real-time information problems, such as sensor unavailability and noise should be addressed (for e.g. St-Cyr, 2006; St-Cyr & Vicente, 2005). These problems, though not inherently in the display, impair the overall performance of the system. Therefore, the design of interfaces should aim to allow for robustness in the face of lossy information and failure of systems. A third requirement is the need to extend interface design in terms of new paradigms and concepts (for e.g. Burns, 2000). Apart from these requirements, there is a necessity for achieving proper technology adoption for EID interfaces in the industry.

Next to EID, the application of CWA in team/organizational design has a few associated challenges (Naikar, 2011, p.20). These include lack of empirical evidence whether CWA produces effective solutions in comparison to other approaches. The lack of empirical evidence stems from the fact that there are constraints on time and resources for conducting such studies in industrial settings. Currently, the techniques are measured in terms of usefulness (impact and contribution) rather than formal procedures. In the future procedures need to be developed for a formal evaluation.

Apart from the above two challenges, a third set appears in relation to design. In a recent survey of views and attitudes on CWA and design, the researchers found that there was no “typical” manner in which the results of CWA were used in the design process (Read, Salmon &

Lenné, 2014). Using a survey-based methodology of open- and close-ended questions, the authors note that the respondents indicate the use of additional processes for design. Further, 57% of the respondents answered that an additional design approach is needed. The authors note that "even three of the six respondents who had applied EID expressed the view that an additional design approach is needed" (Read, Salmon & Lenné, 2014, p. 170). Additionally, beyond interface design, there is the need for providing comprehensive support for design for other applications. The authors (Read, Salmon & Lenné, 2014) are currently presenting different approaches with the intention of presenting a toolkit for design guidance, rather than a strict standardized methodology, for CWA.

A final set of challenges associated with CWA appears in terms of other phases associated with CWA. Taking the example of strategies analysis, Naikar (2011, p. 30) notes that a major challenge includes a set of possible strategies that the workers adopt spontaneously, as well as could adopt if provided adequate support. Therefore, CWA could be extended by other approaches from the field of naturalistic decision-making. Specifically, a recognition-primed decision model can provide insights about decision-making and strategies that experts adopt in a variety of domains. Therefore, other phases of CWA can be extended theoretically as well as empirically with other approaches present in cognitive ergonomics. These above sets of challenges provide directions for further research related to CWA. The above description shows that CWA has been extended theoretically and empirically in multiple ways. Also, opportunities and directions for future research have been identified.

2.3 Themes in present approaches in human technology interaction

The following section presents the various themes present in HCI and HFE to situate CWA in terms of the broader context of research in HFE and HCI. This section also identifies the possibilities of extension of CWA for addressing broader themes related to human technology interaction. Themes are presented because the coverage of all the major theories is simply beyond the scope of this thesis. In HCI (cognitive-focus) there are many dominant theories such as distributed cognition, activity theory, and embodied cognition, among others (see Rogers, 2012, for a review). Similarly, in HFE there are many approaches for considering the cognitive dimension of work. While some researchers emphasize that cognitive engineering is applied cognitive science and turn to cognitive science for theories, others emphasize the need for understanding cognitive processes. Further, in terms of methods, there are a multitude of methods available for conducting cognitive task analysis (for e.g., see Hoffman & Militello, 2009, for a survey of cognitive task analysis). Therefore, in order to situate CWA in these broad streams of theories in HCI and HFE and identify possible extensions, in this chapter a few major themes are recounted. These themes are far from complete as the fields are quite broad; however, it is aimed that the major themes address the general direction of thought in HCI and HFE (cognitive-focus).

In order to understand the major trends in theory related to human technology interaction design, the first step is to recognize that both HCI and HFE are different disciplines. HCI has grown out of computer science and has an emphasis on computational technology (for a history of HCI, see Grudin, 2012; also, Myers, 1998). It often draws upon eclectic theories from sociology and anthropology. The most notable journals in this field include “Human Computer Interaction” and the most visited conference in this field is the annual ACM CHI (Association of Computer Machinery Computer Human Interaction) conference.

In contrast to HCI, HFE lies halfway between psychology and engineering (for a history of HFE, see Meister, 1999). The emphasis on HFE is not limited to computers but is broader, ranging from military applications to environmental design. Further, HFE often addresses domains that are not typically captured by HCI, such as risk management and safety. For HFE, computers are just one technology. The Human Factors and Ergonomics Society (HFES), USA, has twenty-three technical groups ranging from aerospace to virtual environments. “Computer Systems” is just one technical group among these various groups in HFES. Moreover, in contrast to HCI, HFE often draws its theories from psychology and biomechanics. The most notable journals in this field are “Human Factors” and “Ergonomics”. The most visited conference in this field is the HFES conference. As a result, both HFE and HCI disciplines have very little interaction even though at times, they often work on similar problems.

Along with these distinctions involving disciplinary conventions, the two fields overlap in their methods of data gathering. For example, in the area of cognitive task analysis, HFE practitioners often use many techniques such as interviews, and observations, among others for "knowledge elicitation" (see Cooke, 1994 for a review); whereas, HCI deriving from theories of sociology employs ethnographic research involving interviews, and observations, among other approaches. However, due to different backgrounds of the fields, even though they use similar approaches, the manner in which the content of analysis is approached differs. Since both these disciplines present insights, a common set of themes are highlighted that appear in the disciplinary literature of HCI and HFE (cognitive-focus), which will be used for generically understanding the major ideas related to interface design. Specifically, nine major themes are highlighted for discussion: embodiment; situatedness; embeddedness; knowing and acting as an inherently socio-cultural process; environment-person interaction as the unit of analysis; knowing and acting as intertwined; complexity; user and operator; and technical-rational vs. actor-based approach to modeling.

2.3.1 Embodiment

Embodiment came into vogue with the demise of standard cognitive psychology (information processing psychology). With the growth of embodied cognitive science (Clark, 1997), there was a growing need for understanding the role of the body in relation to the mind. Embodied cognitive science emphasizes the primacy of the role of the body in the process of knowing and acting. In HCI, "embodied interaction" was addressed by Dourish (2001, 2013) to serve as a foundation for future HCI research (see Svanæs, 2013a, 2013b, for an extended view of this approach). Embodied interaction draws from two perspectives — tangible computing and social computing. Social computing is based on the application of insights from sociological approaches (for e.g., ethnomethodology) for design of interaction; whereas, tangible computing links computing with physical design. Dourish notes that both tangible and social computing perspectives share a common background. Along with these two areas, Dourish also draws extensively from the phenomenological approach of the philosopher Heidegger for addressing the everyday "being in the world". Thus, he links the technological world and the body in its everyday social milieu. Embodiment is a paradigm that is already widely accepted in mainstream HCI. For the design of human technology interaction, the concept of embodiment will play a central role and should be taken into account while designing whole-body natural interfaces. In HFE the emphasis on embodiment is lacking. Even though, since its inception, HFE has addressed the body (in terms of biomechanics and anthropometrics) in a sustained manner, the distinction between mind and body still remains in HFE - physical ergonomics and cognitive ergonomics. As a result, the embodied perspective that the mind can only be understood in relation to the body has still not obtained due emphasis.

2.3.2 Situatedness

The concept of situatedness entails the understanding of knowing and acting based on circumstances in which people find themselves. As circumstances change, new opportunities arise; as a result, people comprehend the changing circumstances and formulate potential lines of actions. The term “situatedness”, however, does not imply that knowing and acting are merely reactive. Rather, situatedness implies that rational planning and foresight would not be enough to completely characterize human knowing and acting. Therefore, along with the rational planning, local contingencies have to be addressed in order to understand human knowing and acting comprehensively.

With the demise of standard information psychology, HCI researchers turned towards sociological theory. Prominent among these theorists was Suchman (1987). Using the theoretical and sociological approach of ethnomethodology, Suchman conducted a study on how people interact with photocopiers. She highlighted how the knowing and acting of those people was shaped by the local contingencies and constructed in situ. Suchman’s perspective has gained widespread acceptance in HCI (also see Dourish & Button, 1998, for ethnomethodology). Similar to Suchman’s view of situated action, activity theorists (see Kapetilinin & Nardi, 2006, for HCI; Norros, 2004 for HFE) have also highlighted the situatedness of action. Beginning from the cultural-historical school of thought based on the Soviet psychologists, Vygotsky and Leontev, activity theorists conceptualize activity in terms of ongoing improvisations in the flux of work. Further, researchers ascribing to the “Situated Learning” (Lave & Wenger, 1991) perspective also highlighted the situated nature of knowing and acting. By discussing the ethnographic studies conducted on apprenticeship of Yucatec midwives, Vai and Gola tailors, naval quartermasters, meat cutters, among others, Lave and Wenger (1991) highlight that knowing and acting is inherently situated and develops in an ongoing manner as the circumstances evolve. In short, HCI theorists recognize the situated nature of human knowing and acting and design for situatedness. In HFE the situated perspective is reflected by Norros (2004) and Vicente (1999). Both authors emphasize that situatedness is important for understanding human activity. Vicente uses the term “context-controlled variability”, gained from ecological psychologists following Nikolai Bernstein. However, CWA (Vicente, 1999) can be extended to account for situatedness pertaining to everyday social interaction. The social dimension of situatedness is not completely captured by Bernstein’s use of the term “context-controlled variability” which was more attuned to the aspects of motor-control rather than social situatedness.

2.3.3 Embeddedness – Person and environment as the basic unit of analysis

The idea that the person is embedded in the environment and the person-environment system should serve as the fundamental unit of analysis is present in both HCI and HFE, albeit in different ways. The psychologist J.J. Gibson championed the environment-person mutuality as a basic unit of analysis of human knowing and acting. Gibson highlighted that to understand psychological phenomena comprehensively, the person should be understood in relation to the environment. Beginning with a phenomenological perspective, Gibson characterized the environment in terms of what it affords the person, for good or for ill. Gibson’ views have gained widespread acceptance in both HCI and HFE. The person-environment unit of analysis is crucial as it is in consideration of this level of analysis that the behavior becomes intelligible. Just as the embodiment approach stresses that the mind cannot be addressed without the body, similarly, the embedded approach highlights that behavior can be systematically studied in context. In HFE, researchers (for e.g., Bennett & Flach, 2011; Norros, 2004; and Vicente, 1999) recognize the person-environment system as a basic unit of analysis. However, the *reciprocity* between the person and environment can be emphasized further in CWA and made salient for extending it further to account for a deeper engagement with the work domain. Reciprocity would allow for the mutual interchange between the person and the environment. In HCI, in general, the person-environment unit of analysis is more widespread but remains subtle. For example, the idea of the person-environment system can be gleaned from Gaver (1996) as well as Dourish (2001) in their treatment of Gibson’s ecological psychology. Further, the interaction of the person and the environment is also present in other theoretical approaches adopted in HCI such as situated action (Suchman, 1987), distributed cognition (Hutchins, 1995) as well as activity theory (Kapetilinin & Nardi, 2006).

2.3.4 Knowing and acting as an inherently socio-cultural process

Sociologists, anthropologists and cross-cultural psychologists have highlighted that knowing and acting are fundamental socio-cultural processes. They can only be understood in the socio-cultural milieu in which the person actively participates and gains sustenance. HCI researchers have actively accounted for incorporating this perspective in their theories. HCI approaches relating to sociology (for e.g., Star & Strauss, 1999; Suchman, 1987, 2007) have addressed the need for design of artifacts based on addressing human knowing and acting as a fundamentally socio-cultural process. Similarly, cultural-historical activity theorists regard activity as a socio-cultural process (Kapetilinin & Nardi, 2006, Ch. 3). The anthropologist Hutchins (1995) uses the example of the operations conducted aboard a ship. In this example, Hutchins highlights that it takes the whole crew in the cockpit to navigate the ship. Hutchins highlights that the process of knowing and acting is inherently social as well as organizational. Similar emphasis on knowing and acting as a social process is provided by the anthropologists Lave and Wenger (1991). In their studies on apprenticeship, they have highlighted that the nature of human knowing and acting is fundamentally socio-cultural. To summarize, HCI theorists acknowledge human knowing and acting to be a fundamentally socio-cultural construct. In contrast to HCI, in HFE the socio-cultural view of human knowing and acting is muted. This is due to the fact that psychology, as compared to sociology, holds sway in HFE. As a result, HFE composed of psychologists and engineers retains its views on basic cognitive processes as separated from sociality; whereas HCI with its underpinnings in sociology treats human knowing and acting as fundamentally social.

2.3.5 Knowing and acting as intertwined

The idea of knowing and acting as intertwined processes is stressed by two main sources—symbolic interactionist and ecological psychology perspectives. Both these approaches stress that human knowing can only be addressed coherently by conceptualizing it in terms of acting. Picturesquely stated by an ecological psychologist, Turvey (2007, p.6), perception (knowing) and action (acting) form a Mobius strip. It is extremely difficult to parse where one ends and the other begins. Further, a stronger claim made by ecological psychologists is that knowing is only possible because it has developed with action (for e.g., Goldfield, 1995). To address any behavior would entail understanding how the interplay of knowing and acting takes place in any given situation. In HFE, Bennett and Flach (2011) have addressed Gibson's views and have treated knowing and acting as intricately entwined and have used it as a foundation for designing interfaces. Similarly, Norros (2004) has also addressed knowing and acting as intertwined in any given situation and has developed the core-task analysis. In HCI, in general, the intertwined view has been treated subtly as compared to HFE. For example, in HCI this view can be gleaned by the proponents of ecological psychology such as Gaver (1996), and Dourish (2001, 2013), among others.

2.3.6 System-orientedness

HFE is a discipline with its foundations based on the concept of systems (Meister, 1996). Adopting a systems approach involves taking a holistic view on problem conceptualization and solving for human-machine systems. Typically, since the technology in HFE ranges from nuclear power plants to air-traffic systems, adopting a systems approach allows for handling multiple actors as well as different intertwined technologies. Further, all these various aspects, attributes and elements are handled together in a common systems framework, allowing for addressing faults and failures as a part of the overall system. In taking a holistic stance towards human-technology interaction, the impact of non-obvious variables is revealed. The system-orientedness in the field of HCI remains muted. This may be due to the scope (computers) and the development of HCI as a field (see Grudin, 2012; Myers, 1998), among others.

2.3.7 Complexity

Complexity refers to the property of the system in which changes in one part of the system causes unintended changes in another part as well as the overall system (for e.g., Bar-Yam, 2002). Due to its emphasis on large and mid-scale systems, the emphasis on complexity is quite pronounced in HFE. HFE researchers have addressed complexity in large and mid-scale systems in a variety of ways drawing insights from general systems theory, cybernetics and complexity theory, among others (for e.g., Flach, 2012; Hollnagel, 2012; Nemeth, 2012). A perennial problem for HFE researchers is harnessing and controlling complexity to reduce accidents and system failures. This requires optimization for building better systems as well as risk management for building safer systems. In contrast to HFE, complexity is largely absent in HCI research. This is due to the HCI focus, typically, on small scale ICT research and product design.

2.3.8 User and Operator

Operators work under the constraints of correct functioning, designed into the machine by the designer; whereas, in case of the users, the intentions of the users are paramount and they are not bound completely by the constraints of correct functioning as the designer envisioned it. Thus, users, as compared to operators, are more flexible about how the technology is employed. An example presented by Vermaas and colleagues (Vermaas, Kroes, van de Poel, Franssen, Houkes, 2011, Ch. 5) shows how pilots are operators in the air-traffic system; whereas, the passengers are users of the air traffic system.

The above distinction between operators and users is largely absent from discussions in HFE or HCI. Further, the term operator is prevalent in HFE, whereas user is prevalent in HCI. This is partly due to the kinds of technologies being addressed by both factions. HFE addresses a broad range of technologies ranging from nuclear power plants to aircrafts, whereas HCI has a focus on computers. Some researchers (for e.g., Shepard, 2001, p. 245, note 4; Vicente, 1999, p. 12, footnote 1) highlight that the two terms are different labels used by different groups for denoting the same concept. However, for multiperspectival view both are required for addressing systems design to account for the different roles of people involved.

2.3.9 Technical-rational vs. Actor-based approach to address design

Two main ways of modeling are prevalent in systems engineering—actor based and technical-rational [1](de Bruijin & Herder, 2009). The technical-rational perspective is rooted in systems engineering disciplines, whereas the actor perspective was rooted in social sciences. Both these

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[1] The authors (de Brujin & Herder, 2009) use the term “system” and “actor” perspectives. The authors note that the “system” perspective is technical-rational. I have used the term “technical-rational” to minimize the confusion with the use of systems in general, as used in this chapter.

perspectives have their own strengths and weaknesses; they were also similar to and different from each other in many respects. In HFE, with its system-orientedness, the technical-rational perspective is more predominant. As a result, the emphasis is on understanding subsystems and their behavior differently as well as a whole. System aggregation and decomposition models are devised to understand the behavior of the system; typically, the system and subsystems are modeled with a view of rationality. Modeling is best characterized as an analytical activity; thus, a separation between the analysis of the system and subsequent intervention is often possible. Since systems often tend to be complex, models addressing complexity facilitate a better understanding of the system. Once insight into system functioning is obtained, the optimization procedure is formulated. In short, in this technical-rational perspective, modeling is a testable activity. In HFE, the technical-rational perspective is quite prevalent. This may be due to the emphasis on engineering as well as psychology, construed as a natural science.

In contrast to the technical-rational perspective, an actor perspective is predominant in HCI. In the actor perspective, actors have different types of interdependencies and mutual as well conflicting interests. Actors are reflective and adopt strategies to negotiate situations. The flux of decision-making cannot be neatly divided into phases, as interaction between modeling and intervention is often fluid and moves beyond the imposed categories. The typical manner of addressing systems behavior is in terms of actors as well as sub-networks and a network-of-networks. The networks allow for understanding how information flows and decision-making is possible in a multi-perspectival scenario. Further, in the actor perspective, it is often difficult to separate analysis and intervention as clearly as in the technical-rational perspective. Actor behavior, being strategic and reflective, often thwarts technical-rational model making. In short, modeling in the actor perspective should capture the intense negotiation that comprises strategic and reflective actor behaviors. The actor perspective is widely prevalent in the social sciences. In HCI, which derives many of its theories from social sciences, the actor perspective in systems design is predominant for (actor based approaches can range from situated action concepts to actor network theory, see Rogers, 2012, for a survey).

2.4 CWA in relation to the main themes

Once the above concepts have been delineated, they serve as a basis for situating CWA in the broader trends of HFE and HCI research and identifying possible extensions. The table (Table 2.1) charts the various themes presented above and lists HFE (cognitive-focus) and HCI's views in relation to the major themes. The table also situates CWA in relation to these major themes; thus, providing a broader understanding of WIDF in terms of the themes already prevalent in human-technology interaction design.

Major themes	HCI	HFE	CWA	Proposed extension
Embodiment (Cognition as an embodied concept)	Prominent	Minimal	Absent	Possibilities for extension
Situatedness	Prominent	Present	Prominent	Prominent. However, could be developed further for social situatedness
Embeddedness	Prominent	Present	Prominent	Prominent. However, could be developed further to make the *reciprocity* between person and environment salient
Knowing and acting as an inherently socio-cultural process	Prominent	Negligible	Absent	Possibilities for extension
Knowing and acting as intertwined	Prominent	Present (but minimally)	Not explicit	Possibilities for extension
System-orientedness	Negligible	Prominent	Prominent	Prominent
Complexity	Negligible	Prominent	Prominent	Prominent
User and operator	User	Operator	Common term to capture both operator and user—worker—for sociotechnical dimension of	Possibilities for extension to account for both user and operator

			systems	
Technical-rational and Actor-based approaches for systems design	Actor-based approaches are prominent	Technical-rational approaches prominent	Technical-rational approaches prominent	Possibilities for extension to account for both approaches

Table 2.1: CWA situated in the themes of HCI and HFE. Possibilities of extension of CWA have been highlighted

2.5 Need for extending CWA in terms of fundamental principles

Primarily, there is a need to CWA for novel technologies that require the conception of people as embodied, embedded and situated constructs. Such technologies require theoretical viewpoints and conceptual tools to elicit design requirements. Therefore, as it will be shown in the next chapter, WIDF provides these viewpoints from action theory (Bernstein[2]) to address the embodied and embedded dimensions. Also, symbolic interactionism (Blumer) is used to provide the integral dimension of treating people as inherently socio-cultural situated entities. Both the embodied view and the socio-cultural situated views are incorporated with CWA's fundamental assumptions (based on Rasmussen and Gibson) in order to produce WIDF.

2.6 Conclusion

The aim of this chapter was to present a brief survey of CWA and situate it in the larger currents of thought in HCI and HFE (cognitive-focus) research. It was highlighted that CWA can be extended in terms of embodiment and treating human knowing and acting as intertwined and an inherently socio-cultural process. This can be done by addressing fundamental viewpoints related to action theory (Bernstein) and symbolic interactionism (Blumer). Further extension is possible for CWA by formation of new hierarchies based on Rasmussen's AH; thus, accounting for the embodied, embedded and situated constructs of everyday behavior. In the next chapter the aim is to show how CWA can be extended fundamentally for the embodied, embedded and socially situated aspects of human knowing and acting.

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[2] Even though CWA references Bernstein in a few places related to action, the link between Bernstein, body dexterity, situated action and ecological psychology is not substantiated (see Vicente, 1999, p.70, 358, 359 for references to Bernstein). In other words, even though CWA has rudiments of Bernstein's approach, its relation to the body is not theoretically incorporated in the framework. WIDF extends Bernstein's approach with CWA to provide a broader conception of embodiment in human knowing and acting.

Chapter 3: Extending CWA—WIDF

3.1 Introduction

In this chapter, the main goal is to extend CWA in terms of the proposed framework, WIDF. WIDF is based on the approach of CWA and extends it for extracting design requirements. The current chapter is divided into two main parts. The first part provides the basic theories and sets up the stage for constructing the framework. The second part delves into the actual construction and presentation of the proposed framework, WIDF.

In chapter 2, while delineating the past research on CWA, a few areas of concern were highlighted. Specifically, there was a need for a framework to address the people as embodied agents, embedded in a socio-technical milieu. In order to design for the embodied and embedded behavior of people in engineered systems, it is important to consider these aspects in a detailed manner. This is done by drawing from four theoretical backgrounds — engineering, psychology, physiology and sociology. The first approach is of the engineers K. Vicente and J. Rasmussen; J.J. Gibson's ecological psychology is the second approach; the Russian neurophysiologist N.A. Bernstein provides the third; while the fourth is H. Blumer's Symbolic Interactionism from sociology.

Together these theories are invoked to addresses the design challenges raised for addressing human knowing and acting as an embodied, embedded and situated construct. The choices of these theorists are strategic as they provide the basis of addressing human knowing and acting in a sustained manner, as well as share common insights. As it will be shown later, Gibson's approach provides the basis for knowing and acting as an intertwined process. In addition, it allows for the treatment of behavior as a systemic concept linking both the person and the environment. Bernstein's approach shares a common theoretical outlook with Gibson and addresses the role of the body and activity in a detailed manner. Thus, Gibson and Bernstein's theories together serve as the foundation for addressing the embodied and embedded dimension of human knowing and acting. Along with Gibson, Blumer also addresses knowing and acting as situated concepts. Moreover, Blumer stresses that the people and their milieu should be understood as a situated *social* construct; i.e., behavior should take into account the *intersubjective* dimension of lived experience. Thus, Blumer's approach allows for a fuller treatment of the social aspects of human interaction in technological environments. Finally, all the above insights are put together with the engineering approach of Rasmussen and Vicente to produce WIDF for requirements gathering.

A second reason for the choice of these four theorists is that they have already received widespread attention in the HCI and HFE community and their theories have served as the basis for the development of tools and frameworks. For example, Rasmussen and Vicente's CWA approach is widely acknowledged in the field of HFE and has provided the basis of work modeling approaches (e.g., Goodstein, Anderson & Olsen, 1988; Vicente & Rasmussen, 1990; Vicente, 1999). Gibson's approach has been developed by interaction designers, such as Gaver (1996). Specifically, Gibson's notion of affordances is a widely used concept in interaction design (Norman, 1988). Bernstein's view of activity and its applicability to interaction design has been highlighted by activity theorists (for e.g., Kaptelinin, 1996, p.111; Kaptelinin & Nardi, 2006, p.183). Finally, Symbolic Interactionism has also been developed as a theoretical approach in interaction design (for e.g., Star, 1998). In the next step the basic insights of the four approaches are presented and will be used for developing WIDF.

3.2 Background approaches for developing WIDF

WIDF is a framework for providing requirements for the design of advanced interaction for embodiment, embededness and situatedness. The primary concern for the designer is to design for the everyday reasoning of the people involved in these sociotechnical systems. In short, the design caters to their knowing and acting in situations that are routine as well as non-routine.

Human knowing and acting have been the subject of study for aeons. Philosophers, psychologists, sociologists, legal theorists, political theorists, economists and not to leave out the literary theorists and artists, have addressed, debated, and scrutinized the concept of human knowing and acting. The author of this thesis, though awed by the multitude of perspectives and millennia of debates, adopts an engineering epistemological approach to the problem. Due to the influx of new technologies, future work environments are expected to provide ubiquity, pervasiveness, and seamless integration of technologies in everyday sociotechnical activities. As a result, human interaction with this “invisible” technology will be in terms of a naturalistic embodied mode. Specifically, the whole body will be involved in an adaptive intelligent interaction with the everyday technological environment. Design of such an interaction with the technical milieu will require an emphasis on not only the role of the body but also its relation with the environment. Developments in psychology have illuminated cognition (more broadly knowing and acting) as an embodied and embedded concept that should be addressed in a situated manner (for e.g., Clark, 1997). Similarly, sociologists have emphasized that the study of human knowing and acting can be approached in situated and processual terms (for e.g., Prus, 1996). Thus, a primary aim in this thesis is to address human-technology interaction from an embodied, embedded and a situated perspective.

In adopting the engineering approach, the main theoretical core of this thesis derives from CWA (Vicente and Rasmussen). CWA adopts an engineering-based functional perspective for studying the everyday activity of the operators in nuclear power plants. The approach used by Rasmussen and Vicente (Rasmussen & Vicente, 1990; Rasmussen et al., 1994, p. 32,70) is compatible with the theories of the ecological psychologist, J.J. Gibson, on human knowing and acting. Gibson’s primary area of research was perception and action. More broadly, his functional relational approach has provided themes for addressing knowing and acting in general. Complementary to Gibson’s functional relational perspective is the approach adopted by the sociologist H. Blumer. Blumer presents Symbolic Interactionism as a sustained perspective for studying human knowing and acting and emphasizing its social dimension. Even though they have been developed in different disciplines, Blumer’s Symbolic Interactionism can serve as a complementary approach to Gibson’s perspective. This is partly due to the common roots of both their perspectives. Both theorists derive concepts from the philosophical school of pragmatism. Blumer’s approach involves the concepts put forward by the pragmatist philosopher G.H. Mead (Hammersley, 1989; Prus, 1996); whereas, Gibson’s intellectual lineage hails from the pragmatist philosopher and psychologist W. James (Heft, 2001). [3]A study of human knowing and acting cannot be understood bereft of the role of the body and its dexterity. A study of the body and dexterity allows for developing fully the understanding of human knowing and acting in a

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[3] Even though the individual pragmatists differ in their approaches, they do share a common outlook (see Thayer, 1968, for an exposition on the various viewpoints and theorists in pragmatism).

sustained manner. In order to study the body, the approach of a physiologist, Nikolai Bernstein, is presented. The proponents of Gibson's approach view Bernstein as a natural complement for the study of activity.

All four of these approaches highlight some useful criteria required for devising this framework. It is to be accentuated that even though this framework derives from all these four perspectives (Gibson, Bernstein, Blumer and Rasmussen, Vicente) it should not be considered as the direct application of these approaches. Nor is there any attempt to theoretically synthesize the approaches of these theorists. Rather, the aim is to use the concepts provided by these theorists to develop a novel design framework, WIDF. The next step begins with briefly recounting the fundamental themes that form the basis of CWA.

3.2.1 CWA's approach (Rasmussen and Vicente) - emphasis on engineering epistemology

Over the course of his career, Rasmussen proposed a framework for addressing systems design. This framework takes into account the dimension of function-structure linkage, correct functioning and also accounts for human activity in technical contexts. Rasmussen's primary goal was to support the operator's traditional ways of knowing and acting in the technical context of nuclear power plants. The problem that Rasmussen approached was the reliability of nuclear power systems; i.e., how to ensure that the nuclear power system was functioning correctly for the specified conditions and duration of time.

In studying the problem, he found that the human element was crucial to system reliability. Further, due to the influx of digital computers as a medium for controlling the power plant functioning, the challenge for Rasmussen and the Risø group was to develop concepts that would aid in systems design for supporting operator activity. For this reason, Rasmussen and his research group conducted several field studies on operators' and electronic troubleshooters' activities. From these studies, they emphasized that the traditional ways of knowing and acting of the operators have to be supported. This traditional knowing consisted of a unique notion of "process-feel". The operator approached any situation based on a generic intuitive understanding that had been gained from experience; thus having a generalized "feel" for the situation. This intuitive understanding was also found in electronic troubleshooters during the activity of fault finding and repair of electronic equipment.

In order to account for the traditional “process-feel”, Rasmussen formulated a model of the human as a systems component, as a part of the overall system. In trying to address operator decision making, he found that experts behaved differently from novices; specifically, experts made intuitive leaps during the reasoning process. To address the behavior of novices as well as experts, Rasmussen incorporated new knowledge structures, such as the decision ladder. Further, he stressed the need for addressing strategies that the operators adopt in conducting their work. Rasmussen found that operators are attuned to routine situations; however, non-routine situations, even though rare, put extensive demands on the operator. In order that operators successfully handle both routine and non-routine situations, the designers need to address the operator’s cognitive activity. Rasmussen reasoned that to address operator knowing and acting in situations, the designer had to share an interpretative understanding of the operator’s activities. In other words, the designer needs to understand the situation as the operator views and acts in it.

Another key insight was that as the event unfolds, operators use multiple ways in understanding the scenario. Often they shift between various construals in order to cope up with the situation. Therefore, in order to support operator knowing and acting, these multiple constructs, or mental models, have to be brought together at various levels of abstraction. Further, since these abstractions were of a technical system, the integrity of correct functioning of the system had to be accommodated. Rasmussen used the concept of correct functioning and philosopher Polanyi’s reasons and causes to formulate the AH. Also, Rasmussen used the AH both as a structure for conceptualizing the various categories of models involved in system representation, as well as using the AH as an abstraction decomposition space for charting the mental activities of the operators. In this chapter, WIDF will be based on the AH as used in terms of consolidation of various categories rather than as a decision space for charting the activities of operators and users.

Similar to the categories used for representing the system in AH, Rasmussen also addressed human performance in terms of multiple categories. According to Rasmussen, any activity required an understanding in terms of motor skills, rules governing behavior and knowledge categories (SRK taxonomy) that enable the person to cope with the situation. Thus, the performance of the individual is best viewed in light of the person's goals and expectations. Rasmussen regards humans as goal-oriented systems. Being goal-orientated, people have their reasons for acting in a particular manner. Rasmussen emphasizes that for systems design this view of reasoned activity needs to be addressed in terms of generic categories rather than specific instances. This formulation of the human activity in terms of generic categories led Rasmussen to address its linkages with perceptual meaning, and more broadly, symbolism. Following the philosophers Cassrier and Whitehead, Rasmussen recognized the human as a symbol-manipulating animal. Rasmussen linked the generic categories of performance with perceptual content. In doing this, Rasmussen used Whitehead's distinction between signals, signs and symbols, corresponding this with the categories of skills, rules and knowledge. Thus, Rasmussen linked meaning-making along with generic categories of human performance.

In a book on cognitive engineering in 1994, Rasmussen along with his colleagues (Rasmussen et al., 1994) distilled many of the main ideas of the past decades of research into a comprehensive framework for the engineering analysis, design and evaluation of advanced information systems. In the 1994 book, the ideas originally presented in Rasmussen's 1986 book were extended for sociotechnical systems. Specifically, Rasmussen and colleagues (Rasmussen et al., 1994, p. xi) "seek an optimal combination of a conceptual basis with a practical and realistic sense for 'what it is really like out there.'" The authors adopt a functional perspective along with a focus on qualitative models to address modern work systems. They mention that at a systemic level, work systems act as self-organizing adaptive systems and are dynamic in nature. Thus, Rasmussen et al. (1994) adopt a technical-rational perspective towards systems modeling (further developed in Rasmussen, 1997, see Brujin & Herder, 2009 for difference between technical-rational and actor-based approaches). In their approach, they stress the modeling of purposes and associated constraints. These systems have goals and constraints that are implicitly reflected in the practice and customs inherent in the operator's work activity. The authors acknowledge the inherent variability in human behavior. Human behavior has a history based on the decisions and choices that have been made. These choices have been made in the presence of other alternatives. Even though the alternatives were not selected, these potential choices remain hidden in the work activity. From the perspective of design, these potential choices are meaningful as they provide an insight into the possibilities of activities and challenges that shape the behavior of the work system as a whole. The authors conclude that in order to design work systems, there is a necessity for systemic characteristics of work to be supported; as well as the need for supporting human performance criteria that ultimately end up shaping the system's behavior. In other words, the authors acknowledge that along with the systemic dimensions, human activity as a situated concept should also be addressed for systems design. Rasmussen's approach has also been manifested in detail in terms of EID (Vicente & Rasmussen, 1992) and CWA (Vicente, 1999).

To conclude, the following main insights are gleaned from CWA's approach to support the development of WIDF: engineering knowledge structure; AH and correct functioning (Polanyi's reasons-causes); functional approach; technical-rational perspective on systems modeling; focus on situations; focus on qualitative categorical descriptions; and the designer adopting an interpretive understanding of the operator. As mentioned before, CWA (1999) draws on Gibson's (1979) theories; therefore, the next step addresses Gibson in greater detail.

3.2.2 Gibson's approach - emphasis on knowing and acting as an intertwined and ecological process

The study of perception and action (more broadly, knowing and acting) underscores Gibson's entire approach[4]. His approach to knowing and acting, known as ecological psychology, is a broad area of research. Therefore, from the purview of this thesis, a few important aspects of Gibson's ecological psychology will be addressed in detail: how knowing and acting function as intricately entwined; how knowing and acting function as an ecological systems concept; the

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[4] Gibson conceptualized the problem of knowing and acting based on his ecological approach. For him, "Knowing is an extension of perception" (Gibson, 1979, pg. 258). Moreover, on the idea of concepts, Gibson says that concepts that are used as descriptions can be understood as knowledge made as "*explicit* instead of *tacit*". He further states: "Perceiving precedes predicating" (Gibson, 1979, pg. 260). But concepts do not provide a complete description of the flux of the activity the perceiver is involved in. Thus, to understand concepts one has to understand the ongoing flux of actual events. Thus, for understanding knowing and acting, percepts and concepts have to be taken together.

reciprocity between the knower and the environment; and the focus on holism and hence the avoidance of dualisms.

J.J. Gibson was a psychologist working on the problem of perception. Specifically, Gibson was interested in visually guided activity. Researchers in human factors are aware of his study on automobile driving as well as studies in aviation during World War II (for e.g. Bennett & Flach, 2011; Rasmussen et al., 1994). In a career spanning several decades Gibson provided not only a different approach to the study of visual perception but also laid the groundwork for a different approach to psychology. Fundamentally, Gibson considered perception and action as intertwined processes that are the product of the co-evolution of animals within their environments. In the course of a millennia of evolution, the perceptual and action systems of the body have been shaped to opportunistically take into account the meaning and values[5] embedded within the environment. Therefore, Gibson espouses the idea that knowing and acting *can only be* understood in relation to the environment in which it occurs. This relation has three interrelated aspects - the animal, the environment, and the reciprocal interrelation. Reciprocity is a key term in Gibson's thought. Reciprocity indicates the existence of "distinguishable but mutually supported realities" (Lombardo, 1987, p. 3; also see Costall, 2001). Using the notion of reciprocity, Gibson addresses the animal in its environment in terms of a holistic system. Modern knowledge systems are rife with dualisms (Costall, 1995, 2012): subject-object; mind-body, perception-action; nature-culture; and knower-known, among many others. The science of psychology like other sciences draws on these various dualisms. In contrast to these various dualisms, Gibson used the concept of reciprocity to achieve a holistic approach. Reciprocity provides a scientific meaningful basis for the study of knowing and acting (see Gibson, Reed & Jones, 1982 for detailed exposition on the need for reciprocity and realism).

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[5] For Gibson values were real properties of the objects of the environment. Gibson coined the term affordances to account for values: "When the constant properties of constant objects are perceived (the shape, size, color, texture, composition, motion animation, and position relative to other objects), the observer can go onto detect their *affordances*. I have coined this term as a substitute for values, a term which carries an old burden of philosophical meaning. I mean simply what things furnish for good or ill. What they afford the observer after all depends on their properties" (Gibson, 1966, p.285).

Linked to reciprocity is Gibson’s stress on the notion of an ecosystem. Gibson’s approach was to understand perception and action as ecological concepts; i.e., the perception and action of animals could only be understood in terms of relation with their environments. Since animals have evolved within their environments for millennia, Gibson states that an animal-environment ecosystem is the correct unit for analysis of psychological phenomenon. The co-evolution of the animal and its environment has reciprocally shaped the animal and its environment in such a manner, so that the environment is meaningful for the animal.

Gibson, deriving from evolutionary theory and functional psychology, views the mind in terms of adaptive “functions”: the way in which animate life is adapted to the environment to sustain itself. However, the stress on adaptation should not imply that there is a unidirectional fitting of the animal to the environment. As mentioned before, animals and environments are reciprocal concepts, mutually shaping each other. They have to be viewed as wholes. The animals adapt to the environment as well as appropriate it to their purposes. The animals act towards the environment based on the meanings and values present in their environment. In other words, the environment affords certain activities for the animal. Therefore, affordances of objects of the environment can only be known *in relation* to the animal.

It is important to note the stress on the term ecology rather than merely the environment. “Ecology is the scientific study of the *relationship* between organisms and environment” (Smith & Smith, 1998, p. 3, emphasis mine), whereas “environment includes not only the physical conditions but also the biological or living components that make up an organism’s surrounding” (Smith & Smith, 1998, p. 3). Thus, the mere presence or absence of the environment is not sufficient. In order to understand behavior as an ecological concept, the relationship between the animal and environment has to be studied. Therefore, the use of ecological psychology is to emphasize this relationship; in other words, ecological psychology presents a functional-relation perspective on understanding behavior. In terms of ecological psychology, the animal is immersed in its life-world, constantly knowing and acting. Knowing and acting (perception and action) are two sides of the same coin. It is an ongoing process in which the animal is involved constantly. The animal in its environment requires a further clarification. For Gibson, the mind was an embodied and embedded concept. Avoiding the traditional mind-body dualism, Gibson recognized the mind as emerging out of the activities of the embodied animal in its environment.

To envision the interaction between the animal and the environment better, the concept of a niche is necessary. A niche is a particular place occupied by the animal in its ecological settings (Gibson, 1979, p. 128, emphasis in original):

> “Ecologists have the concept of a *niche.* A species of animal is said to utilize or occupy a certain niche in the environment. This is not quite the same as the *habitat* of the species; a niche refers more to *how* an animal lives than to *where* it lives. I suggest that niche is a set of affordances.
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> The natural environment offers many ways of life, and different animals have different ways of life. The niche implies a kind of animal, and the animal implies a kind of niche. Note the complementarity of the two. But also note that the environment with its unlimited possibilities existed prior to animals. The physical, chemical, meteorological , and geological conditions of the surface of the earth and the pre-existence of plant life are what make the animal possible . They had to be invariant for animals to evolve.”

Along with the niche and the notion of “how” of living (emphasis on processual approach), Gibson provided the concept of “affordances” as a cornerstone of ecological psychology. Affordances are value-laden properties of entities of the environment that are present for the good or ill of the animal. For Gibson, the environment of the animal consisted of affordances. As an example to demonstrate the concept of affordances, a hermit crab is considered. The hermit crab is a crustacean with a soft abdomen. It often “adopts” a shell for its body and to retract itself from its predators. Thus, a shell should afford certain properties that are meaningful for the crab. This shell will not have the same meaning for any other species of animals such as fish. Further, when the hermit crab outgrows its shell, the shell loses its value for protection. The hermit crab then searches for another shell. This example is given to underscore the basic fact that meaning is a relational concept that can be studied in terms of the animal and its environment and the meaning the animal has for its environment. Further, affordances are not static but change over time. They do not simply belong to the object but also to the animal, and have to be understood from the animal’s perspective. An ecosystem can hold multiple animals. Even though they share the same life-world, animals interact with their environments differently—they occupy different niches. A fish and a frog share the same pond, but their activities and meaning for the pond may be in stark contrast with each other. For Gibson, the environment is what affords animate life. Affordances are relational concepts that bridge the traditional dualism of subjective and objective. In Gibson’s (1979, p.129) own words,

> “An affordance cuts across the dichotomy of subjective-objective and helps to understand its inadequacy. It is equally a fact of the environment and a fact of behavior. It is both physical and psychical, yet neither. An affordance points to both ways, to the environment and to the observer.”

It is also to be noted that Gibson, being a *direct realist*, did not envision affordances to be a static property of the object. An object can have multiple affordances based on the animals interacting with it as well as the context. Further, the affordances are not psychical qualities changing on the whim of the observer, these are realistic properties of the environment. An animal may or may not perceive or attend to the affordance of the environments based on its need but the affordance which is actually an invariant is still present. To make this point clear Gibson (1979, p.137, emphasis in original) adds,

> “Note that all these benefits and injuries, these safeties and dangers, these positive and negative affordances are properties of things *taken with reference to an observer* but not properties of the *experiences of the observer*. They are not subjective values; they are not feelings of pleasure or pain added to neutral perceptions”

A particular point to be noted in the discussion till now is the biological terminology of animal and environment. Even though Gibson recognized humans as different from other species, his focus was on studying psychology as related to the science of ecology. Therefore, the terminology used by Gibson emphasized the natural science aspect. Since this thesis presents design framework for human technology interaction, instead of the animal and environment, people and their work environments are emphasized. However, even though Gibson emphasized psychology as a part of ecological science, the notion of the socio-cultural dimension of human life was central to Gibson’s approach (Reed, 1996). Gibson acknowledged the centrality of the social for a theory of knowing and acting (Gibson, 1950, p.154-155): “Social learning is inevitably moral, in an elementary sense of the term, and it is probably a mistake first to construct a behavior theory without reference to social interaction, and then to attach it only at the end”. Gibson’s stress on the social dimension of human knowing and acting is shared by the sociologist Blumer and serves as the basis for accounting for the social dimension of behavior.

From this brief discussion of Gibson’s approach, a few important aspects are raised for the upcoming framework. First, the worker and his environment are to be considered as reciprocal entities, together taken as a whole. Second, perception and action (knowing and acting) are ongoing processes that the person is constantly involved in. Third, the same environment can hold multiple people and social roles. Due to their backgrounds and varied experiences, these people will interact with their environments differently. The environment holds different meanings and values for different individuals. These individuals occupy different niches in the environment. These niches involve the consideration of meanings and values that have evolved over a period of time, as well as changing due to the persons’ interaction with the environment.

To conclude, Gibson provided an ecological approach to the study of knowing and acting. In contrast to the traditional theories of psychology, Gibson promulgated an approach where the mind, more specifically, human knowing and acting, is treated as an embodied and embedded concept — an ecological reality that sustains knowing and acting. Gibson’s approach was succinctly summed up by another ecological psychologist, Mace (1977):”Ask not what’s inside your head, but what’s your head inside of”. Gibson’s ecological approach has been extended by other ecological psychologists, notably by R. Shaw and M. Turvey. Specifically, they have extended Gibson’s approach by drawing parallels with the approach of the Russian physiologist Nikolai Bernstein. Over a number of years, Bernstein developed an account of the body and activity in terms of “physiology of activity”, which is described next.

3.2.3 Bernstein's approach - emphasis on embodied dimension of knowing and acting

A study of the human knowing and acting is incomplete without an understanding of the body and its relation with the environment. Traditional psychologists espouse the dualism of mind and body, relegating activeness to the mind and reducing the body to a passive mechanism. However, as viewed by both Rasmussen and Gibson, mind and body are both intimately involved in knowing and acting. In order to highlight the role of the body and its dexterity, the approach of the Russian physiologist Nikolai Bernstein is discussed. Bernstein’s view on activity is compatible with the already existing activity theory view of psychology. Further, activity theorists have highlighted the role of Bernstein for developing interactive systems (Kaptelinin, 1996, p.111; Kaptelinin & Nardi, 2006, p.183). Bernstein’s approach is further selected due to two main reasons.

First, the current proponents of Gibson’s ecological psychology view Bernstein’s approach as complementary (Shaw, Mace & Turvey, 1996, p. ix). The stature of Bernstein’s approach is compared to Gibson’s approach by the ecological psychologists, Reed and Bril (1996): “Had Bernstein's *On Dexterity* been published as scheduled, around 1950, it would have offered a powerful companion piece to Gibson’s emerging ecological analysis of perception” (p.432). Further, along with the ecological psychologists, Rasmussen also recognizes the complexity of activity and uses Bernstein’s approach in discussing skilled human performance. Rasmussen’s references Nikolai Bernstein’s 1967 book *The Coordination and Regulation of Movement* to describe the control of voluntary activity (Rasmussen, 1983, p. 259).

Second, the principle idea in Bernstein’s approach is the “physiology of activity”. In this view, Bernstein (1967, 1996) avoids the traditional view of the body as a reactive mechanism. For Bernstein, the active body should be understood in its environmental context. The environment not only serves as the context for meaningful activity but also constrains the activity. Specifically, along with the bodily forces required for activity, the environment provides the extra-personal forces (for example gravitational forces), which shape activity.

A primary problem which Bernstein addressed was the construction of movements: “*Live movement is a ball of entangled interactions*” (Bernstein and Popova, 2003, p.12, my emphasis). In understanding everyday goal-directed activity, Bernstein posited a “motor image” of the goal. Rather than being mentalistic, this “motor image” was the orientation of the body towards the goal stage. The goal stage could be reached by the animal in its environment, a joint influence of bodily and extra-bodily forces generating activity *in situ*. Thus the goal-directed activity is not brought about by any straightforward direct connection by the nervous impulses, rather, it was holistically constructed by both local and global contingencies shaping behavior.

Bernstein’s approach has been formulated and extended by ecological psychologists; therefore, the larger aspects of his approach will not be delved into here in great detail. However, his hierarchical levels that construct activity will be addressed, as they provide a necessary foundation for understanding the role of the body and its relation to activity. In case of HFE and HCI, as devices become smaller and embedded, interaction with them will be more naturalistic and understood in terms of the whole body. Bernstein's approach allows for the design of whole body naturalistic interactive systems.

Bernstein's approach was directed towards the understanding of activeness, as opposed to reactiveness; and organism, as opposed to mechanism. In trying to understand the construction of goal-directed movements, Bernstein formulated the problem in the following manner: how do the various physiological parts, each having multiple degrees of freedom, come together to produce higher order structures for the control of action (Turvey, 1990; Turvey, Shaw, & Mace, 1978). In other words, how does qualitatively *simple* behavior arise from multiple physiological parts of complex biological systems? This question, also known as the degrees of freedom problem (discussed later in this section), needs a *functional, dynamic,* and *kinematic* approach for its solution. In order to connect the three, Bernstein's (1996) solution was to provide a *hierarchical* view for the construction of actions (A-D): tone, muscular-articular links (synergies), space and action, respectively.

Bernstein, while studying the body and dexterity of activity, divided the construction of movement into four levels (A-D): tone, synergies, space and action. The level of tone is the first level that supports all other levels of the body. It is a deeply seated level that Bernstein (1996) terms as the "backgrounds of all backgrounds" (p. 115).This level also links the humans to their primal lineage and to all other animals. The lowermost level of tone supports the next level of synergies, which level B corresponds to. Synergies are muscular-articulator links. These links often work together dividing the body in terms of a functional system based on the context of activity. This level allows for automating movement and formation of motor skills. Typically, the level B is supported by the level A in its endeavors. In turn level B supports level C, the level of space.

Building on the level B of synergies of muscles and related physiological entities, the third level of space allows for accounting for the contact between the whole body and the environment. At his level of space, the linkage of the body to the whole psychological experience is being linked to the environmental context. The level of space provides the person a sense of "*spaciousness, stationariness and homogenity*" of the surroundings (Bernstein, 1996, p. 134, emphasis in original). This level of space also allows for the perception of the objects and their dimensions such as shapes, angles, directions and the relative spacing from each other. Thus it is real and not merely corresponding to one's private experience. At this level, movements of whole body transference in space, such as walking and running, take preponderance. The ability of the level C allows for treatment of objects in terms of meaningful wholes based on the close cooperation between the sensory apparatus as well as the holistic experience. Thus, this level of space is necessarily abstract. It pervades in a manner such that one is able to translate the representation of an object in space in terms of specific combinations of muscles required to reach and grasp it.

Finally, the level of actions, level D, consists of chains of meaningful actions that allow for complex activity to emerge. The level of actions provides the necessary dexterity and completeness that was not present in the level of space. This level is also special as it is not to be found in all animals. Bernstein calls this level, "the human level" as it indicates the presence of activity, typically not found in other animals. At this level the human is able to merge together various complex and voluntary actions (Bernstein, 1996, p. 146):

> "First of all, it is necessary to explain what we mean by actions. Actions are not simply movements. Most of them are whole sequences of movements that together solve a motor problem. Each such chain consists of different movements that replace each other systematically, leading one to a solution for the problem. All the movements, parts of such a chain, are related to each other by meaning of the problem. If you miss one of the links of the chain or mix up their order, you will fail to solve the problem.
>
> Let us consider the very simple but impressive example of lighting up a cigarette. A smoker takes a cigarette pack out of his pocket, opens it, selects a cigarette, kneads it, and puts it between the lips; then he opens a matchbox; takes out a match; glances at it to check if its head is intact; turns the matchbox; strikes the match once or several times, as necessary, until it ignites; turns it so that the flame flares up; if necessary, protects it from wind; moves it close to the cigarette; sucks the match's flame into the cigarette; extinguishes the match; throws it away; and eventually puts all the things back where they belong."

Bernstein’s description of this act of lighting the cigarette shows the immense complexity involved in even the seemingly simplest of daily activities. Crucial to this level of actions is the presence of the human hand. Bernstein mentions that the human hand is in a close relation to the higher regions of the brain and there is highly developed reciprocity between the two.

In describing the role of the body in relation to action, Bernstein also introduced the concept of the image of the required future. Roughly translated it meant a probabilistic understanding of the goal state. From a psychological perspective such an image was not mentalistic but was a “motor image” i.e. *it was an orientation of the body towards the goal stage*. Thus, Bernstein linked action towards the goal psychologically without making it mentalistic in nature,

> “The goal . . . conditions the processes that have to be united in the concept of goal-directedness. The latter incorporates the entire motivation of the struggle of the organism for the attainment of the goal and leads to the development and strengthening of goal-conforming mechanisms of its realization. And the entire dynamic of goal-directed struggle by means of goal-conforming mechanisms is a complex that is brought together most correctly by the term ‘activeness’.” (Bernstein [Bernstein], 1990, p. 454–55, as quoted in Veresov, 2006, p.8).

In selecting this “image of the future” Bernstein characterized activity as directed towards an object. Hence, the strict boundary between the psychological and physiological is best understood as fluid. Bernstein’s four levels are necessary for understanding the body and its related performance in human knowing and acting. Thus, the body and the performance cannot be separated but should be addressed together for a complete understanding of situated activity.

From Bernstein’s account, a few aspects are gleaned for constructing WIDF: situatedness of activity; considering of the body and performance together for a conceptualization of activity; formulating acts in terms of a hierarchy of levels in order to provide a fine-grained approach for performance; and considering the intentional aspects of the act as a relational ongoing process linking the person to the environment. In summary, a discussion of Bernstein’s account allows for the development of the role of the body and activity in systems design. Specifically, it allows for understanding how goal-directed behavior can be characterized more broadly in terms of the body and its capabilities, as well as its relation to the environment; i.e. a situated concept. The notion of activity as situated, among other concepts, is also addressed in detail by Blumer, described next.

3.2.4 Blumer's approach - emphasis on knowing and acting as a fundamentally intersubjective process

After providing a description of the three theorists, the approach of Herbert Blumer is discussed below. Blumer's approach of Symbolic Interactionism is addressed for three main reasons. First, Blumer provides the necessary emphasis on human knowing and acting as an inherently social process. Second, Blumer's approach emphasized qualitative understanding and the development of situated concepts as a necessary aspect of understanding conduct. Third, in developing concepts, Blumer emphasized the necessity for understanding the viewpoint of people under consideration, as well as understanding the world through their perspective.

Herbert Blumer, a social scientist, developed the approach of Symbolic interactionism[6]. In doing this, he derived insights from the interpretive tradition in sociology and the pragmatist philosophy of George Herbert Mead (Blumer, 1969/1998; Hammersley, 1989). Blumer provided a methodology for addressing human knowing and acting taking into account the richness of lived experience as well as the rigor of scientific method (Braugh, 1990). Thus, Blumer linked the interpretive and ethnographic traditions and underscored the intersubjective nature of lived experience (Prus, 1996). Blumer recognizes that human conduct is shaped within a matrix of shared interactions; in short, human life is group life. Understanding group life is to categorize human knowing and acting in terms of being activity-oriented, (multi) perspectival, reflective, negotiable, relational and processual (Prus, 1996). In broadly characterizing human activity as the above, Symbolic Interactionism has emerged as a sustained perspective on addressing group life and has been used for studying a variety of domains of activity:

> "Let me begin by identifying the empirical social world in the case of human beings. This world is the actual group life of human beings. It consists of what they experience and do, individually and collectively, as they engage in their respective forms of living; it covers the large complexes of interlaced activities that grow up as the action of some spread out to affect the actions of others… . The empirical world, in short is the world of everyday experience, the top layers of which we see

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[6] Symbolic Interaction is an approach developed in great detail in sociology. Details of the history and background of this mode of analysis can be found in Prus (1996) and Hammersley (1989). See Baugh (1990) for details of the Blumer's approach. Also see Bulmer (1984) for a broader understanding of interactionism from the Chicago School of Sociology.

> in our lives and recognize in the lives of others… Ongoing group life , whether in the past or the present , whether in the case of this and that people, whether in one or another geographical area, is the empirical social world of social psychological sciences" (Blumer, 1969/1998, p.35)

A central problem for Blumer was the search for addressing the intersubjective formulations of everyday knowing and acting for the development of a reflective social science (Braugh, 1990, Ch. 1). In considering the unique aspects of social beings, Blumer (1969/1998) notes that human interaction is a formative process. People are continually defining, redefining, negotiating, rejecting, ascertaining, constructing meanings of objects and other people as well as their own selves. As a result, human beings are immersed in a universe of changing meanings — a symbolic universe. The meanings in this universe are to be accounted for in terms of ongoing activity:

> "It calls attention, first, to the fact that the essence of society lies in an ongoing process of action-not in a posited structure of relations. Without action, any structure of relations between people is meaningless. To be understood, a society must be seen and grasped in terms of the action that comprises it. " (Blumer, 1966, p. 541)

To address the rich symbolic universes in which people dwell requires a methodology for comprehending the ongoing inter-subjectivity as well as the objectivity of these universes. Thus, the methodology must understand human conduct in a variety of situations as a social construct:

> "A society is seen as people meeting the varieties of situations that are thrust on them by their conditions of life. These situations are met by working out joint actions in which participants have to align their acts to one an-other. Each participant does so by interpreting the acts of others and, in turn, by making indications to others as to how they should act" (Blumer, 1969/1998, p.72).

In understanding the lived experience of the people under consideration, a social scientist should take into account the viewpoint of these people and view their worlds from their perspectives. This view is based on the social scientist Charles Horton Cooley's notion of "sympathetic introspection". "Sympathetic introspection" involves understanding other people and their symbolic universes from their viewpoints (Prus, 1996, p.51). In other words, in order to develop a coherent understanding of the people under consideration, they have to be treated as intentional and moral agents involved in their everyday practices and the scientist has to understand their world through the perspective of those people. In other words, the aim of the scientist is to develop an “intimate familiarity” with the subject matter under consideration; as well as a generalized understanding of the state of affairs and its ongoing development. To achieve this generalized understanding, Blumer emphasized qualitative research as the proper mode of analysis of human interchange and subjectivity:

> “Symbolic interaction involves interpretation, or ascertaining the meaning of the actions or remarks of the other person, and definition, or conveying indications to another person as to how he is to act. Human association consists of a process of such interpretation and definition. Through this process the participants fit their own acts to the ongoing acts of one another and guide others in doing so” (Blumer, 1969/1998, p. 66)

For studying social life, based on a qualitative enquiry, Blumer asks the social scientist to note that meanings are shaped by the social milieu, and the individual, in attending to the milieu, uses an interpretive process of dealing with the ever changing meanings associated with the milieu. To address the unique nature of social life, Blumer proposed the fundamental approach of Symbolic Interactionism:

> “Symbolic interactionism rests in the last analysis on three simple premises. The first premise is that human beings act toward things on the basis of the meanings that the things have for them. Such things include everything that the human being may note in his world — physical objects, such as trees or chairs; other human beings, such as a mother or a store clerk; categories of human beings, such as friends or enemies; institutions, as a school or a government; guiding ideals, such as individual independence or honesty; activities of others, such as their commands or requests; and such situations as an individual encounters in his daily life. The second premise is that the meaning of such things is derived from, or arises out of, the social interaction that one has with one's fellows. The third premise is that these meanings are handled in, and modified through, an interpretative process used by the person in dealing with the things he encounters” (Blumer, 1969/1998, p.2)

In acknowledging the premises of symbolic interactionism, Blumer stresses on the notion of acquiring data and developing concepts in a contextualized manner. The final concepts emerge from a constant refinement. The scientist acquires the data based on an interpretative understanding and forms preliminary concepts. As more data is acquired, the original concepts are refined to provide a better insight into the subject matter under consideration. This close interaction between data and concepts allows for a robust understanding (Blumer, 1998, Chs. 9-10; also see Braugh, 1990, Ch. 2). These concepts developed in one domain of activity can also be further extended for a trans-contextual analysis between various domains, giving rise to generic concepts for understanding human knowing and acting (Prus, 1997).

The most important aspect of using the approach of symbolic interactionism, for WIDF, is its emphasis on individual activity being understood from the larger scale of embedding the context of meanings and values. In other words, human life is socially shaped and can only be understood in terms of the larger underpinnings of group life. Further, the important aspect of the interpretation in studying group life is that the researcher shares an insight with the person being studied; i.e., adopting the stance of sympathetic introspection to achieve an intimate familiarity with the subject matter under consideration. This method of sympathetic introspection is crucial for designers, as they have to understand the perspective of the people for whom they are designing. Further, Blumer's insistence on sympathetic introspection is also observed in Rasmussen's approach. Even though Rasmussen does not use the term "sympathetic introspection", his method of investigating troubleshooting behavior is highly similar to the approach espoused by Blumer. Along with sharing perspectives, Blumer and Rasmussen both acknowledge the qualitative mode of analysis for addressing human knowing and acting. Along with these similarities with Rasmussen's method, interactionist research has provided a sustained theoretical perspective for the field of interaction design. Specifically, in HCI, interactionist researchers have provided a theoretical background for understanding the basis of human knowing and acting in information systems (for e.g. Star, 1998; Vaske & Grantham, Ch. 4).

In this thesis, the interactionist perspective provides the first step of WIDF. As it will be explained later in detail, using the theoretical viewpoint of symbolic interactionism and a qualitative mode of analysis, an interpretive understanding of the work context is achieved. Along with using the qualitative mode of analysis in this thesis, the primary aspect to be highlighted from this discussion of Herbert Blumer and symbolic interactionism is the focus on conceiving human activity as being intelligible only when considered as a part of a larger universe of social meanings.

3.2.5 Salient aspects of human knowing and acting for systems design

Till now, four approaches have been discussed in relation to human knowing and acting. Each of these approaches has highlighted some key aspects of human knowing and acting, aspects that are implicit but not delved into in detail by the other approaches. At the same time, these approaches are selected because they share common meta-theoretical assumptions[7].

First, all these approaches acknowledge the uniqueness of human knowing and acting. To begin, Rasmussen recognizes a human as a symbol-making creature and acknowledges the distinction between signals, signs and symbols in human performance. Along with Rasmussen, Blumer begins with the symbolic universe in which humans are immersed. Gibson and Bernstein both accept that humans differ from other animals. Further, the goal-oriented activity of humans, based on meaning provided by the environment, is different from other animals. Thus, there is a necessity for accounting for the symbolic nature of human knowing and acting.

A second common thread that runs through the four approaches is the intertwining of knowing and acting. For Rasmussen, knowing and acting are intertwined processes. His distinction between signals, signs and symbols and their correlates of skills, rules and knowledge highlight this important aspect of his approach. Similarly, Blumer acknowledges that knowing and acting are conjoined and ongoing. Activities often open up novel avenues for knowing which in turn require new ways of knowing. Similarly, Gibson and Bernstein's approach demonstrates that purposeful transactions of people with their environments are underwritten in a common currency; i.e., the transactions of knowing and acting are two faces of a same coin.

The third notable aspect of all these approaches is that the notion of behavior can only be satisfactorily understood in terms of its relation to the environment. The theorists treat the person-environment as a unified system based on which any study of behavior is to be promulgated. For Rasmussen, the operator and his environment were the basis for studying and devising his framework. For Gibson, the person-environment system served as the beginning for

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[7] Gibson and Blumer draw from the pragmatist tradition and many common concepts can be traced back to the pragmatists. Ecological psychologists view Gibson and Bernstein's approach as naturally complementing each other. Further, Rasmussen references both Gibson and Bernstein in developing his approach.

the study of knowing and acting. For Bernstein, activity had to be characterized not only in terms of the body but also in terms of the extra-bodily forces for a concerted and sustained view on action. Similarly, for Blumer, people cannot be studied separate from the social milieu in which they exist.

The fourth common aspect of all the four approaches, also following from the third, is that the people under consideration are acknowledged to be *immersed* in their surroundings. Thus, human knowing and acting should not only be addressed in terms of person-environment unified system but also in terms of the human being in relation to their environment. Therefore, people are *enveloped* in a universe of meanings that are constantly in a flux (a processual emphasis). All the four theorists study the *embodied and embedded activity of people in their meaningful environments*. Rasmussen devised his engineering knowledge structures in trying to understand the work environment from the worker's point of view. Blumer stresses the necessity of understanding the world of the people from their viewpoint. The interactionists following Blumer have extensively stressed the necessity of understanding the everyday world as a *situated* enquiry into human knowing and acting. Finally, for both Gibson and Bernstein, the people under study are enveloped in meaningful environments. Gibson's concept of affordances underscores the necessity for understanding human knowing and understanding in relation to the environment viewed from the person's perspective.

Apart from these similarities, these various approaches bring some unique aspects that are conducive for the development of the proposed framework, WIDF. Rasmussen's approach focuses on technical contexts. It highlights that the design of technical systems is the linking of function and structure along with correct functioning; hence, it presents the basis for the engineered dimensions of the proposed framework. Gibson's approach highlights the notion of viewing the behavior not only in terms of the person *and* the environment but also from the perspective of the person *in* the environment. Therefore, the environment is not only meaningful for the person but also presents possibilities of action. In short, the environment has use-value for the person involved in the situation. Bernstein's approach, which is complementary to Gibson's approach, highlights the role of the body and the construction of activity. Further, activity is understood in terms of not only bodily forces but also extra-personal forces such as gravity, which play a major role in activity. Thus, Bernstein's approach provides the necessary linkage for human knowing and acting to be treated as an embodied concept. Finally, Blumer's approach highlights the social milieu that serves as a background for all human knowing and acting[8]. Humans grow and develop in a symbolic universe of shared and negotiated meanings that are constantly appraised during the course of activity. After the discussion of similarities and differences between the two approaches, the requirements for the design framework are detailed below.

3.3 Requirements of an engineering framework | Design engineer in relation with the subject matter

After the similarities between the various theoretical approaches have been discussed, they are now put into the context of the framework. In the present chapter the need for embodied, embedded and situated viewpoints are extended on the basis of the insights gleaned from the four theoretical approached described above. Further, in this step the aim is to outline the requirements of an engineering framework, WIDF, and the role of the designer in relation to the subject matter under consideration. Both these topics mutually support each other. The design framework cannot be addressed without addressing the designers and their relation to the subject matter under consideration.

The designer shares a dual relationship with the subject matter under consideration. First, the workers are treated as people; i.e., ethical and moral creatures involved in their everyday work activities. In such an approach, the designer shares an interpretative understanding of the worker's perspective — the designer adopts an *intentional stance* (Dennett, 1989). The intentional stance provides emphasis on actor-based approaches to systems engineering. Along with actor-based approaches, the system can be addressed in terms of an engineering-based approach in which the people of the system are treated as parts of a sociotechnical system. In this engineering-based approach, the designer ensures that the overall functioning of the system is correct. Therefore, the designer adopts a *design stance* towards the subject matter (Dennett,

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[8] Rasmussen also acknowledges the social dimension of operator activity in his approach. His treatment of the concept of "error" is especially illuminating in this regard.

1989). In adopting the intentional stance, the designer gives primacy to the actor-based approaches to systems modeling; whereas, in adopting a design stance, the designer stresses a technical-rational perspective in systems modeling. Both these stances are crucial for systems design and the designer balances both these perspectives to ensure proper safety and health to the involved people, as well as the correct functioning of the overall system (Figure 3.1 shows the designer and two stances[9]).

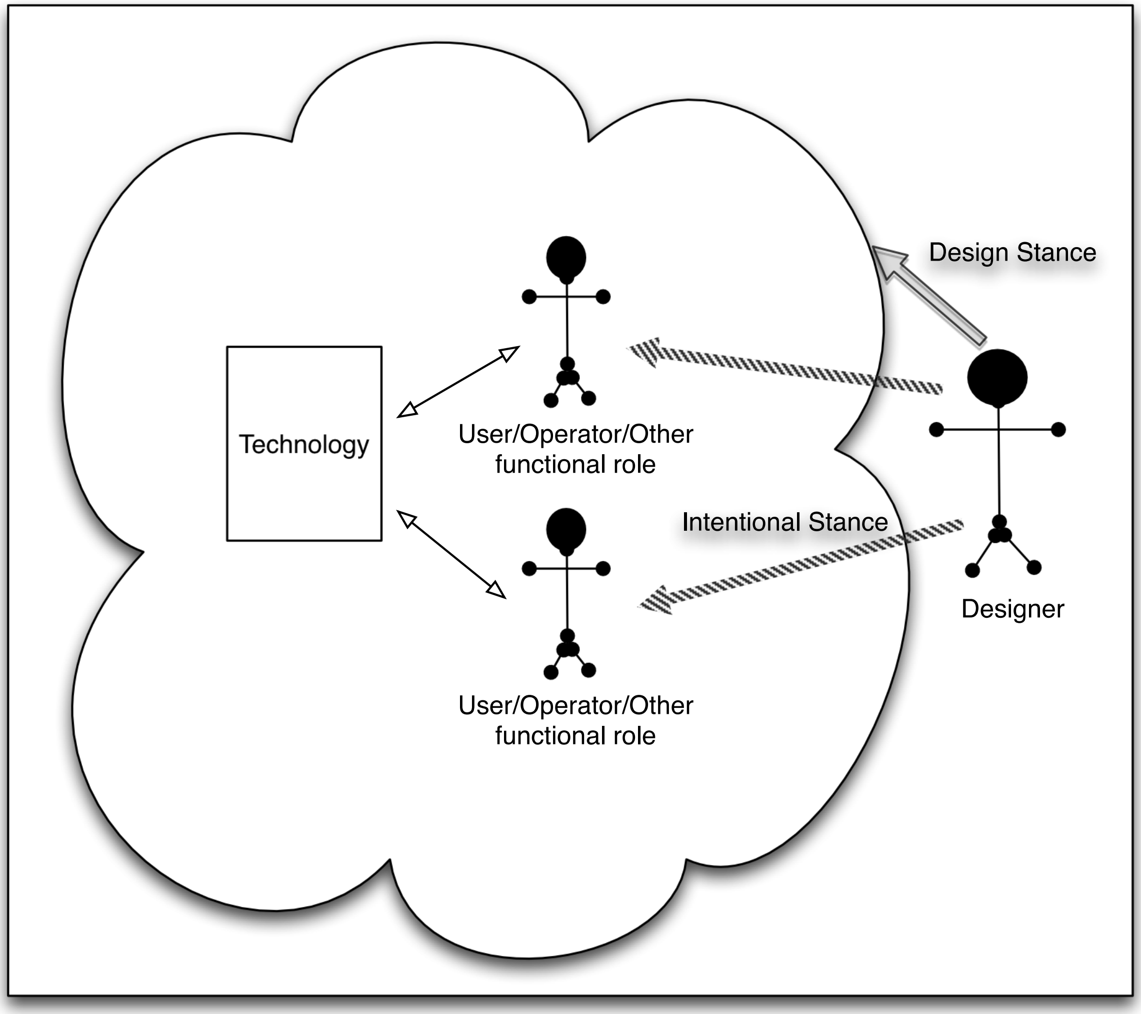

Figure 3.1: Intentional and design stance of the designer with the system under consideration

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[9] Design stance and intentional stance embodies the distinction between technical-rational based approaches and actor based approaches to systems design (see Bruijn & Herder, 2009).

For the design framework to work successfully, a primary requirement is to understand the nature of ongoing activity. From Gibson’s ecological psychology, Blumer’s symbolic interactionism, Bernstein’s activity theory, and Rasmussen’s approach to human knowing and acting, a few insights were brought into relief. First, without being reduced to mechanisms, people form a part of the overall system and the system serves as those people’s environment. In other words there is a need for addressing people as embodied agents embedded in their sociotechnical milieu. This relation between the person and the system puts a theoretical demand on the designer; i.e., the designer should treat the design of the technology as a systemic concept. Focusing on one part, the human or the environment, will render the design at the best meaningless, and at the worst, hazardous. Thus, the aim of the designer should be to design with a focus on the entirety of the situation that unfolds; i.e., taking into account both the human and the surrounding system.

Second, when people are immersed in their everyday work environments, they act meaningfully towards the entities in their surroundings. These meanings are not always preordained but emerge as the events unfold. Thus, people use an interpretive process for modifying the meanings that they have for the objects of their environments. As Rasmussen has shown, supporting this everyday reasoning of the people is extremely essential for both routine and non-routine situations. For designers, the essential message is to design interfaces in a manner so as to support the everyday reasoning for these people in technological work settings.

Third, since the everyday reasoning is functional, it entails a focus on *what* is going on and *how* activities are accomplished rather than *why* things are the way they are. This avoidance of “why” is because a metaphysical viewpoint is avoided in this thesis. From a metaphysical viewpoint, the person may have done what he did because God made him do so, or the presence of aliens, among many other possibilities that explain ultimate possibilities. However, from the viewpoint of the person, the person may have a concrete reason that seemed meaningful at that particular moment. This emphasis on the “what” and “how” is brought about strongly in Rasmussen’s view of errors. Rasmussen points out that errors were after-the-fact labels that were attributed to the operators in question. From the perspective of the operator, the person chose the particular outcome because it seemed meaningful at that point in time. Further, from the study of error reports, Rasmussen found that in most cases the operators knew what to do but at many instances did not exactly know how to accomplish the task. It is not surprising that Blumer, as well as Rasmussen, identify that everyday activity is laced with ambiguities and humans have to make choices in order to circumvent obstacles and accomplish their goals. In order for the people to be successful in their outcomes, the designers should provide the users, operators and other related people with meaningful information in order to avoid mental traps as well as supporting the variability in their activity. Thus, the third aspect brought into relief is the need for the designers in supporting the notion of "what" and "how" of human conduct in order to provide meaningful choices to the people involved.

Fourth, in supporting the functional reasoning of the people, designers need appropriate concepts to represent human conduct. Such concepts should reflect the person's functional reasoning as well as account for the system's correct functioning. Rasmussen used a qualitative approach focusing on generic categories rather than details and quantitative variables. Such a categorical qualitative mode of analysis relates more easily to the operator's reasoning as well as being amenable for systems design. As Rasmussen indicates, formal language understanding involves a focus on variables and causal mode of representations. In case of failures in the system, making changes in formal representations becomes cumbersome, due to the presence of large number of variables and their updating in order to exemplify the changes. In contrast, a natural language description of the system allows for not only accounting for the person's perspective but also for providing a less cumbersome method for accounting for failures. Thus the fourth aspect brought into light is the use of a functional description for characterizing the system.

The fifth aspect to be illuminated was the requirement for treating the human as a symbol-manipulating creature. Humans are creative improvisers that not only adapt to aspects of their environments but also often adopt and appropriate things for their own purposes. These creative symbol manipulators use an interpretative process to negotiate meanings and values in their environment. Therefore, any representation of the work context should support multiple levels of interpretative abstractions. Such an interpretive flexibility is required in dealing with entities because meaning is a relational concept. As discussed by J.J. Gibson's notion of affordances as well as H. Blumer in symbolic interactionism, objects and their meanings can only be considered in the presence of the knowing agent. Rasmussen too deals with the notion of interpretive understanding while employing Whitehead's classification of signals, signs and symbols corresponding to the objects in the environment and human performance. Rasmussen, following Whitehead, mentions that the meaning of the object depends on the context in which it is perceived by the agent. In other words, it depends on the intentions and expectations of the perceiver. The objects of the environment, thus, have meanings and are valuable to the actors based on the situations. The meaning and value of the object may change as the event unfolds. In order to account for the transitions in meanings and abstractions, Rasmussen introduced multiple levels for thinking about a concept. For understanding human performance, he introduced a three-level SRK taxonomy; for understanding the work domain, a five-level AH was introduced. The important insight for the designer is that in order to design robust systems, flexibility in interpretation and abstraction should be provided. From a designer's perspective when the people and the associated technological environment are treated *in toto*, the designer also requires an interpretative understanding to address the system at multiple levels of abstraction. This will allow the designer flexibility in addressing all the aspects of the system. Based on the above insights, the next step is to devise a framework that not only takes into account the design stance but also the intentional stance in dealing with design in work environments.

3.4 Constructing WIDF

3.4.1 WIDF - Step 1

In the first step of WIDF, the designer adopts an intentional stance and treats the people under consideration as intentional agents. In treating people as intentional agents, the designer aims at sympathetic introspection; i.e., the designer tries to understand the symbolic universe of the people involved from their viewpoint. In other words, the designer attempts to decipher how people attend to the milieu based on the meanings they have for their surroundings. Next, the designer recognizes that the meanings are not individualized but have emerged in the process of interaction between the person and the objects in the world, as well as, interchange with fellow beings. The meanings of this symbolic universe are not static but fluxual. The designer takes into account the processual nature of changes in meaning and their associated interpretations. Taking into account the variety of changes in meaning, the designer by a qualitative mode of enquiry aims at a generalized understanding of the subject matter under consideration.

Currently, in this thesis, to understand humans as intentional agents, an ethnographic approach with the background of symbolic interactionism[10] is adopted (see Prus & Mitchell, 2009 for engaging nanotechnology). In this ethnographic approach, the aim is to understand human knowing and acting as ongoing intertwined processes as the challenge for the designer is to design interfaces that will be a part of these ongoing processes. Further, the ethnographic approach is also needed in terms of addressing the various aspects of human lived experience, which affect design indirectly but may not get accounted for in engineering design frameworks. More generically, in this step the designer also acquires a tacit understanding of the work context in a manner that allows for conceptualizing the models in step 2 of WIDF. Since the ethnographic approach, from the viewpoint of symbolic interactionism, has been developed extensively by sociologists, it will not be developed here any further (for a methodological treatment of an ethnography, see Grills, 1998, Prus, 1997, among others). After this first step of WIDF, the designer needs design requirements for these interfaces. These design requirements can be gleaned by conducting an engineering analysis (step 2) from the data acquired in step 1. In step 2, once the models are created and the requirements systematically gleaned, the requirements have to be understood in terms of the larger processes involved in the work domain. Thus, the tacit knowledge acquired in step 1 helps the designer to later utilize the design requirements effectively.

3.4.2 WIDF - Step 2

In step 2 of WIDF, the data obtained in step 1 is used to build engineering models to yield design requirements. In this step, the designer adopts a design stance towards the people under consideration. The design stance considers the people as parts of the overarching systems. Thus, along with the overall system, the parts should also be envisioned as functioning correctly.

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[10] There are many approaches and methods used to conduct ethnographic studies. For e.g. Charmaz, 2006; Lofland, 1976; Glaser & Strauss, 1967. This thesis uses Symbolic Interactionism because of its meta-theoretical similarities to the other theoretical approaches used in this thesis.

Therefore, in this step 2 of WIDF, the correct functioning of the parts is considered based on the design stance that the designer adopts.

Earlier in this chapter, it was emphasized that activities of people are situated in nature. Thus, to approach human beings from the design stance, there is a necessity for considering situations and designing for them from the standpoint of correct functioning. Step 2 of WIDF addresses both these notions and incorporates them for engineering models for interface design.

After discussing the aspects of knowing and acting in work situations, the main components of step 2 are now delineated. These components will be fitted into the categories pertaining to situations in order to yield step 2 of WIDF. The main component of step 2 is the Reasons-Causes-Aggregation Hierarchy (RCAH): RCAH derives from the AH, with which it bears a structural resemblance.

3.4.2.1 Anatomy of the abstraction hierarchy

The AH was discussed in detail in Rasmussen's 1979 paper, "On the Structure of Knowledge — a Morphology of Mental Models in a Man-Machine System Context", and it will be briefly discussed here for developing the framework WIDF. The AH has five levels ranging from physical form to abstract function. These categories have been selected to account for various levels of abstraction and concreteness that the operators and troubleshooters required while conducting their activities. A second point to be noted is that these operators and troubleshooters were working with technical systems (or designed systems) that were expected to function correctly. Therefore, it is not surprising that the categories correspond to a function-structure (form) linkage; i.e., they display the essence of designed systems.

A second important notion for designed systems is the focus on correct functioning. Rasmussen incorporates the philosopher Michael Polanyi's "logic of contrivance" (rules of rightness) to structure the AH. The AH represents designed technical systems linking function to its physical form. Rasmussen retains the use of reasons and causes from his 1979 paper up till 1994 (Rasmussen et al., 1994); also, reasons and causes are present in the background CWA but have not remain subdued (e.g. Rasmussen & Vicente, 1990; Vicente, 1999). A third point to be noted is that after 1985, Rasmussen used the AH along with the dimension of system decomposition (system, subsystem, among others) to produce an abstraction-decomposition space. This abstraction-decomposition space was used to chart the trajectory of the activity of operators, as well as other roles in technical systems (Rasmussen et al., 1994). In *mapping the trajectory* of these individuals, Rasmussen found that operation in a workspace involved using means suited for the intended goals:

> "Operation in a workspace involves an exploration of the available *means* for achieving the immediate *ends*. This exploration includes a *span of attention* dimension connected to *part-whole* considerations, which can range from local components and tools to global features. Thus exploration of a map framed by the dimensions of means-ends and part-whole is a general feature of navigation in a work domain when actors are involved in discretionary tasks" (Rasmussen et al., 1994, p. 37, emphasis in original).

In the present thesis, the formulation of WIDF does not address the person's, (operators and users), trajectory through the workspace. Therefore, unlike the traditional CWA, the extended CWA (WIDF) does not employ the means-ends links. WIDF, like the traditional CWA, can be later extended to consider means ends links for connecting the inter-levels of the RCH hierarchy. However, currently that is beyond the scope of this thesis. In WIDF, the entities in the hierarchy are connected by structural links that show the notion of associations of entities of the various levels; however, these *structural links are not means-ends links*. Not employing the means-ends links does not threaten the integrity of the AH, because the conceptualization of the AH is based on categories of mental models put together by Polanyi's reasons and causes. Therefore, the present extension of the AH takes into account the various levels of AH along with reasons and causes to produce RCH.

3.4.2.2 Reasons and causes

In his paper outlining the AH, Rasmussen (1979) begins with providing a taxonomy of categories of mental models that have been extracted from verbal protocols. According to Rasmussen, "The categories of models stratify the span between the physical world on the one side, and human purposes, i.e., the reason for the existence of the physical systems on the other" (Rasmussen, 1979, p.10; for uniqueness of designed systems in terms of function-structure linkage). Since these categories of models are based on the diagnostic tasks in control rooms and workshops of nuclear power plants, which require an avoidance of malfunctions, the concept of correct functioning is required. In order to address this notion of correct functioning, Rasmussen invokes Polanyi's discussion of "rules of rightness".

The philosopher Michael Polanyi in his book *Personal Knowledge: Towards a Post-Critical Philosophy*, addresses the "logic of contrivance" (Polanyi, 1964, Ch. 11). Polanyi claims that even though the "logic of deductive reasoning" and the "logic of empirical inference" has been present in philosophy, the "logic of contrivance" has yet to make inroads. The "logic of contrivance" refers to the logic by which a tool or machine operates. Any machine is built by embodying operational principles that account for the machine correctly, which constitute the "logic of contrivance".

In contrast to the "rules of rightness" that contrivances (machines, technical equipment and the like) use, the pure sciences do not take these operational principles into account. As a result, the pure sciences treat contrivances as "an altogether chaotic ensemble" (Polanyi, 1964, p.329). Polanyi continues, "In other words, *the class of things defined by a common operational principle cannot be even approximately specified in terms of physics and chemistry*" (Polanyi, 1964, pg.329, emphasis in original). The challenge then occurs to properly take into account malfunction. To answer this question Polanyi underscores the difference between a scientific and technical point of view. A technical point of view takes into account operational principles of a machine; whereas, a scientific point of view missing these principles fails to recognize an object as a technical contrivance:

> "The first thing to realize is that a knowledge of physics and chemistry would in itself not enable us to recognize a machine. Suppose you are faced with a problematic object and try to explore its nature by a meticulous physical or chemical analysis of all its parts. You may thus obtain a complete physico-chemical map of it. At what point would you discover that it is a machine (if it is one), and if so, how it operates? Never. For you cannot even put this question, let alone answer it, though you have all physics and chemistry at your finger-tips, unless you already know how machines work. Only if you know how clocks, typewriters, boats, telephones, cameras, etc. are constructed and operated, can you even enquire whether what you have in front of you *is* a clock, typewriter, boat, telephone, etc. The questions: 'Does the thing serve any purpose, and if so, what purpose, and how does it achieve it?' can be answered *only by testing the object practically as a possible instance of known, or conceivable, machines*. The physico-chemical topography of the

> object may in some cases serve as a clue to its technical interpretation, but by itself it would leave us completely in the dark in this respect." (Polanyi, 1964, pg. 330, emphasis in original)

Polanyi then ruminates on the two kinds of knowledge — scientific and technical. He mentions that these two kinds of knowledge pursue alternative routes and are asymmetrical in relation to each other. Viewing a machine from a technical perspective reveals true knowledge of its essential character; however, when viewed from a scientific perspective, even a thorough and detailed examination is provided, it will not provide an insight into the logic of the machine. The challenge, as Polanyi presents it, is to account for correct functioning *as well as* malfunction. In order to account for these two concepts, Polanyi turns to the distinction between reasons and causes. Polanyi mentions that while contriving a machine, which has a function, the designer follows several steps and there is a specific "reason" for all those steps to be executed in that particular fashion which finally gets embodied in the machine.

Even though a scientific focus on the physico-chemical composition of a machine is not enough to specify its correct functioning, it can help to illuminate the situations when the machine malfunctions. A machine incorporates certain operational principles that determine its character but it also relies on the physico-chemical makeup. This physico-chemical makeup contributes to understanding the "causes" of malfunction:

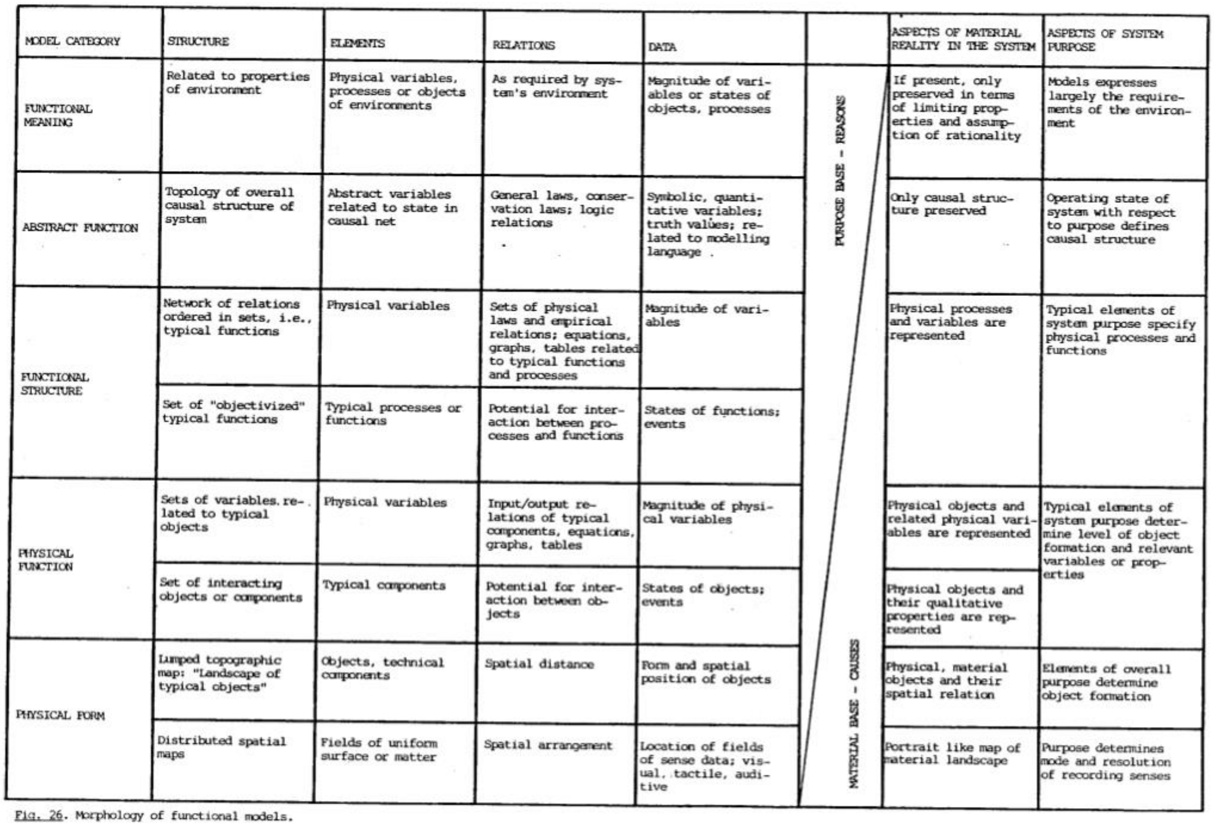
> "Since rules of rightness cannot account for failures, and reasons for doing something can only be given within the context of rules of rightness, it follows that there can be no reasons (in this sense) for a failure. It is best, therefore, to avoid the use of the word 'reason' in this context and to describe the origins of failures invariably as their *causes*. We can say then that physico-chemical investigations of a machine, carried out with a bearing on its operational principles, can elucidate both the conditions for their success and the causes of their failure. It would be wrong to speak of establishing the physical and chemical 'causes' of success, for the success of a machine is defined by its operational principles, which are not specifiable in physico-chemical terms. If a stratagem succeeds, it does so in accordance with its own premeditated internal reasons; if it fails, this is due to unforeseen external causes. (Polanyi, 1964, pg. 332, emphasis in original)

The distinction between reasons and causes is central for Rasmussen's approach as he uses it to structure his hierarchy. Reasons provide an understanding of the manner in which a machine was built to operate; i.e., reasons for its correct functioning. Therefore, it accounts for the machine's purpose or its function. In contrast, the causes account for the machine's malfunctioning. Since causes are dependent on the actual physico-chemical makeup they are closer to the physical form of the machine. Therefore, Rasmussen's representation of the technical devices of the troubleshooters and the operators in the abstraction hierarchy accounts for multiple levels in between the functional purpose and the physical form. The functional purpose of the technical system is linked to its physical form to demonstrate correct functioning by the reasons, which act from the top-down, beginning from the purpose of the machine to its physical structure. In contrast, the causes of malfunction propagate in the opposite direction (Figure 3.2).

3.4.2.3 Description of the levels of AH

Having described the structural organization of the AH in terms of reasons and causes, the next step looks at the details of the different levels. Since a detailed description of the steps has been provided for all the levels in Rasmussen, 1979, here the focus will be limited to a very cursory review of the levels for the development of the hierarchy. Further, the lowermost levels of the physical form will be described in detail as they serves as the basis for developing RCH. The AH consists of five levels. Starting from the lowermost, they consist of physical form, physical function, generalized function, abstract function and functional purpose.

Functional purpose is the topmost level of the AH. At this level, the technical system relates to the environment functionally, in terms of the abstract purpose; in other words, it is bereft of the actual physical instantiation of the system. At the next level of abstract function, the steps are taken towards a less abstract level of description, as compared to the functional purpose. At this second level of abstract function, the aim is to present a unified model of the system, which is abstract and free of material aspects, yet, presents a description in terms of universal laws or symbols. This level can be represented in terms of generalized causal networks of energy, matter and information flows.



MODEL CATEGORY	STRUCTURE	ELEMENTS	RELATIONS	DATA		ASPECTS OF MATERIAL REALITY IN THE SYSTEM	ASPECTS OF SYSTEM PURPOSE
FUNCTIONAL MEANING	Related to properties of environment	Physical variables, processes or objects of environments	As required by system's environment	Magnitude of variables or states of objects, processes	PURPOSE BASE - REASONS	If present, only preserved in terms of limiting properties and assumption of rationality	Models expresses largely the requirements of the environment
ABSTRACT FUNCTION	Topology of overall causal structure of system	Abstract variables related to state in causal net	General laws, conservation laws; logic relations	Symbolic, quantitative variables; truth values; related to modelling language .		Only causal structure preserved	Operating state of system with respect to purpose defines causal structure
FUNCTIONAL STRUCTURE	Network of relations ordered in sets, i.e., typical functions	Physical variables	Sets of physical laws and empirical relations; equations, graphs, tables related to typical functions and processes	Magnitude of variables		Physical processes and variables are represented	Typical elements of system purpose specify physical processes and functions
	Set of "objectivized" typical functions	Typical processes or functions	Potential for interaction between processes and functions	States of functions; events			
PHYSICAL FUNCTION	Sets of variables, related to typical objects	Physical variables	Input/output relations of typical components, equations, graphs, tables	Magnitude of physical variables		Physical objects and related physical variables are represented	Typical elements of system purpose determine level of object formation and relevant variables or properties
	Set of interacting objects or components	Typical components	Potential for interaction between objects	States of objects; events		Physical objects and their qualitative properties are represented	
PHYSICAL FORM	Lumped topographic map: "Landscape of typical objects"	Objects, technical components	Spatial distance	Form and spatial position of objects	MATERIAL BASE - CAUSES	Physical, material objects and their spatial relation	Elements of overall purpose determine object formation
	Distributed spatial maps	Fields of uniform surface or matter	Spatial arrangement	Location of fields of sense data; visual, tactile, auditive		Portrait like map of material landscape	Purpose determines mode and resolution of recording senses

Fig. 26. Morphology of functional models.

Figure 3.2: Morphology of functional models (Reproduced from Rasmussen 1979, p.42). Reasons and causes are used for structuring the hierarchy.

Descending further, the level of functional structure (generalized function[11]) is addressed. Since this level lies midway between the two extremes, it relies both on the functional aspects of entities as well as the physical aspects. This level also presents a gradual transition between one extreme to another. Here the main focus is on the inner aspects of the system. Further, the decomposition is in terms of "standardized" functional elements that are independent of physical and material basis but are derived from their study.

After the third level of generalized function, the next level of physical function is more materially oriented. At this level, the main focus is on the physical properties and functions of

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[11] The labels of the AH have changed from the years 1979 to 1994. However, no major change has been observed in the content of the levels. Specifically, the label for the third level of "functional structure" was changed to "generalized function". Another change to be noticed is that in the 1994 book, Rasmussen and colleagues introduced the notion of physical processes instead of physical functions as the second level from the bottom.

the entities, in terms of interaction with each other. At this level of physical function, the representation is in terms of physical variables and their relations. These physical variables are properties of the objects under consideration. The properties of the individual components are brought together with the variables of other components to form nets of relations.

Finally, at the lowermost level of physical form, Rasmussen makes the distinction between two different submodels —the model of monolithic physical form and the model of structured physical form. The model of structured physical form depends on the intention of the modeler and represents the physical form of objects, as organized physical elements of the larger technical context. The structured physical form often answers the question "where is what" and thus represents the physical form of the components as part of the larger technical context. Since this level is the physical instantiation of the technical system's purposeful functioning, its physico-chemical makeup also makes it the level from which causes of failures act from the bottom-up.

In contrast to the models of structured physical form, models of physical form are considered monolithic if they do not serve as parts of objects or are not structured in other movable objects. Further, at this level the representation is not only dependent on the intentions of the modeler but is also open for being appropriated by the intentions of the user. In other words, due to its physicality it is available for multiple *uses* by other intentional agents in the environments. Rasmussen succinctly summarizes his position on the monolithic physical form in the following manner:

> "This level of modelling of the physical environment is the most objective, i.e., independent of the intentions of the modeller. Even then, however, is it *dependent upon the intended use of the environment* since this determines the resolution (naked eye, microscope, etc.) and modality of senses used for recording the information from the environment. Examples of this kind of model are static scale models, photographic pictures, eidetic imagery, etc." (Rasmussen, 1979, p.11, my emphasis)

The focus on the intended use that an object can have is of special importance here. An object lends itself to multiple uses based on the intentions and experience of the user. In other words, the objects at the level of physical form *afford* certain activities for the user. Even though the worker may not attend to particular affordances of the objects, nonetheless they remain and may be used by other individuals. Rasmussen presents an example of this phenomenon by his example of the electronic circuit (Rasmussen, 1979, p.12, figure 2, reproduced here as Figure 3.3). In this figure, which shows the picture of an electronic circuit, Rasmussen notes that this same circuit will have different meanings for different groups of individuals. For a person unschooled in electronics, the picture will merely remain a photograph of a physical object. However, for a person knowledgeable of electronics, this circuit will be meaningful. Thus, Rasmussen's level of physical form lends itself to an understanding in terms of Gibson's affordances[12]. As mentioned before, according to Gibson's view of affordances, the meaning of the object in consideration (the known) is best conceptualized in terms of the relation of the person (the knower). For example, in case of the electronic example presented above, the electronic circuit *affords* troubleshooting for a technician, who possesses the relevant knowledge. However, the same circuit *does not afford* the same task for a person unschooled in electronics.

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[12] Rasmussen and colleagues have addressed affordances in their 1994 book on cognitive systems engineering (Rasmussen et.al. 1994). In Chapter 4 of this book, the authors present Gibson's direct perception and a cue-action hierarchy in the section on "Cognitive Resources and Preferences of the Actors and Users". In discussing direct perception and affordances, the authors use abstraction hierarchy innovatively to present affordances. In providing this formulation, Rasmussen and colleagues have attempted to capture the notion of affordances and account for direct perception using hierarchies. However, this is not the focus of the present thesis. To reiterate, the aim of the present thesis is to provide an engineering framework, while using this theories from psychology and sociology; but not to use engineering knowledge structures to account for theories of psychology or sociology.

Even though the present thesis does not use engineering structures to account for theories in psychology and sociology, a brief discussion of the innovative attempt made by Rasmussen and colleagues is in order. Since Gibson in his 1979 book alluded to the fact that the world is composed of a hierarchy of affordances, Rasmussen and colleagues used a hierarchy to demonstrate how Gibson's views can be instantiated. The authors also show means-ends mappings along with various levels of abstraction to indicate the connections between the affordances. In this hierarchical representation, the notion of reasons and causes are missing. This is due to the fact that the contents of the hierarchy correspond to natural systems as compared to man-made systems. It is also important to note that Rasmussen and colleagues' levels of affordances have the notion of human implicit in the hierarchy. Highlighting this fact is important as it depicts the hierarchy for affordances as incomplete without referring to whom it is for. As mentioned before, affordances are properties of the environment *in relation* to the animal (person). It follows that a hierarchy of affordances requires an understanding of the person's capabilities. A second aspect to be noted is the label of the hierarchy based on value properties, priorities, and context, among others. These labels implicitly assume a symbol-manipulating animal — in this case, human. Gibson's study of perception and action and thus affordances was aimed at all animals, not just limited to humans. Therefore, Rasmussen and colleagues' innovative attempt to model the hierarchy of affordances should be viewed in light of its focus on humans.

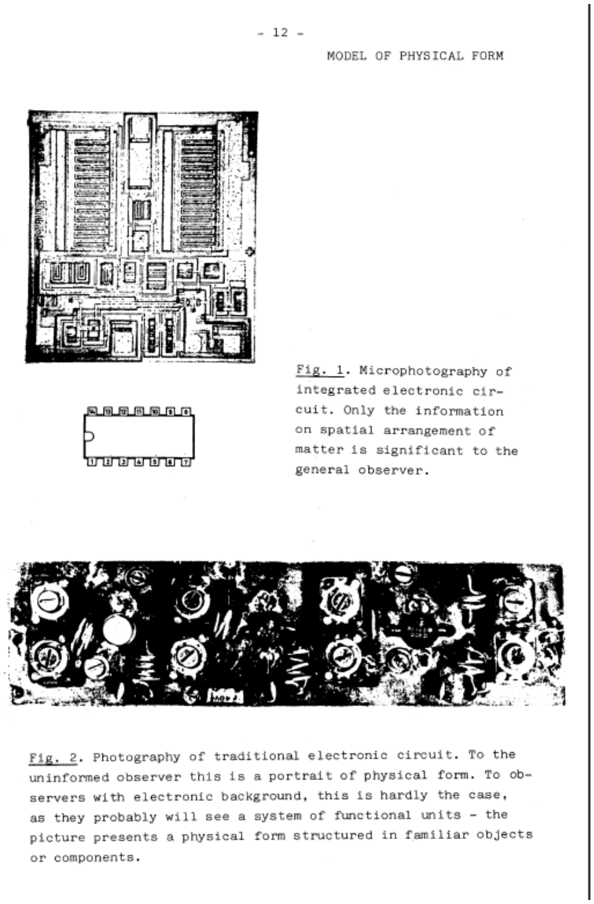
Rasmussen(1979) concludes the discussion of the level of physical form by a consideration of this level for human systems. He mentions that this level may be most amenable for physical actions. However, this level may have implications for cognitive control (p.15):

> "For human data processors, models of physical form probably have most significance for control of physical actions; they may also be needed at the cognitive level when the problem is to judge the spread of the effects of changes in the physical world, because the coupling of events basically depends upon the spatial properties of the environment."

The above-mentioned salient aspects of the level of physical form will be used for developing a new hierarchy for WIDF.

3.4.2.4 Hierarchy; abstraction; and aggregation/decomposition hierarchy

After the description of the reasons and causes, as well as the various levels of abstraction, two important concepts of "aggregation" and "hierarchy" need to be discussed for the hierarchy. Hierarchies are an organization of entities according to some principle. In Rasmussen's approach for control systems design, models were grouped according to their functional descriptions, comprising of functional units having an internal consistency. In case of the abstraction hierarchy, the ordering principle was the notion of "correct functioning" and malfunction (reasons and causes).



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MODEL OF PHYSICAL FORM

Fig. 1. Microphotography of integrated electronic circuit. Only the information on spatial arrangement of matter is significant to the general observer.

Fig. 2. Photography of traditional electronic circuit. To the uninformed observer this is a portrait of physical form. To observers with electronic background, this is hardly the case, as they probably will see a system of functional units - the picture presents a physical form structured in familiar objects or components.

Figure 3.3: Models of physical form. Notice the description accompanying the electronic circuit displayed in figure 2 (Reproduced from Rasmussen, 1979, p. 12)

Since Rasmussen’s aim had always been able to support the operator’s traditional ways of knowing and acting, Rasmussen and Lind (1981) addressed the traditional methods of how operators handle complexity. The notable aspect of this paper is that along with abstraction, the authors introduce the notions of hierarchical thinking in terms of aggregation/decomposition of systems. These concepts of hierarchical thinking and relationships between aggregation and abstraction allows for understanding of the formation of the engineering knowledge structure that forms the basis of the proposed framework WIDF.

Rasmussen and Lind (1981) note that operators use functional properties of the domain during their activity. Such a functional coupling between the entities of the abstraction hierarchy is important as there is autonomy for each entity; at the same time, there is a loose coupling to other functional units at the higher and lower levels. Rasmussen and Lind (1981) derive this concept of internal functional autonomy and loose coupling between two functional units from the complexity theorist Herbert Simon (1996, Ch. 8). Quoting[13] Simon's book, *The Sciences of the Artificial*, they mention the necessity for understanding functional organization of complex systems using the example of the watchmaker presented by Simon.

Simon (1996, Ch. 8) in describing the evolution of complex systems, describes two watchmakers — Hora and Tempus. Hora prospered by building watches made up from a large number of parts, while Tempus lost his business. In order to explain the success of the watchmaker, Simon describes his watchmaking process. The successful watchmaker had designed his watches in such a manner that some elements could be put together in terms of subassemblies. These subassemblies could be put together in larger subassemblies to complete the watch. Simon uses this story to illustrate that in a pragmatic sense, complex systems can be understood in terms of entities that have an internal consistency in a manner that allows for a unit to work sufficiently independently; further, such assemblies are also connected to other functional units via loose couplings. Thus, this manner of connection ensures an internal stability of parts, yet allows for a holistic view of systems connected by the parts (Agre, 2003; Simon, 1996). Rasmussen and Lind (1981) found that from the operator's perspective, the technical system consists of autonomous functional categories that the operators use in coping with the complexity. This discussion of complexity is necessary as it will help in the design of advanced information systems.

Along with the notion of functional assembly, one of the key ideas was the notion of operators dealing with non-routine situations. Addressing non-routine situations was important, as these situations formed a major cause of disasters. Rasmussen and Lind note that highly automated plants have a major portion of routine situations along with rare abnormal conditions (Rasmussen and Lind, 1981, p. 7): "The situation in highly automated plants has very picturesquely been characterised by 99% boredom and 1% horror". To understand the complexity of the unfolding events, routine and non-routine, the operators use several tricks. One of these tricks include understanding the non-routine situation at a high level of abstraction, making choices and then planning detailed activities which will suit the high-level intentional

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[13] A previous edition of Simon's book was quoted by Rasmussen and Lind (1981).

criteria. In everyday work, operators use common natural language reasoning to formulate situations. Common language reasoning advocates a mode of activity in which large groups of physical variables are often aggregated in terms of conceptual entities and their related functions.

Along with this mode of functional diagnosis, another trick that the operators use is to base their judgments on deviations from the normal state. Also, operators do not collect an exhaustive list of data for any situation but often rely on signs:

> “A skilled operator who cooperates with a system has very firm expectations regarding the state of the system, and therefore only looks for signs which are suitable to confirm or disprove his expectations - and only when he has doubts”(Rasmussen and Lind, 1981, p.11).

Even though these signs are effective, in the case of non-routine situations, a diagnosis based on symbols is required. Thus, to cope with these non-normal situations, along with the method of abstraction, the operator also uses a method of hierarchical aggregation/decomposition. This method is used to account for the span of the attention of the operator to the level of detail or resolution required for data processing. Therefore, based on the span of attention the system can be hierarchically aggregated into entities ranging from subsystems to parts. This aggregation is done alongside the abstraction. This abstraction aggregation coupling and the different methods of representation are shown in the next two figures (Figure 3.4, Figure 3.5).

This simultaneous activity of abstraction and aggregation allows the operator to cope with complex situations. In terms of actual problem solving, both the dimensions are required. Therefore, to support such an activity, the designers would have to produce a knowledge structure that takes into account both these dimensions. Thus, in terms of the proposed knowledge structure, the dimensions of abstraction (vertical) and aggregation/decomposition (horizontal) are incorporated for a fuller understanding. It is to be noticed that the aggregation of the system was conceptualized based on the operators’ attention span. In case of designers, who extend the aggregation to other aspects of acts and people, the decomposition will depend on the demands of the work contexts and the scope of design activity.

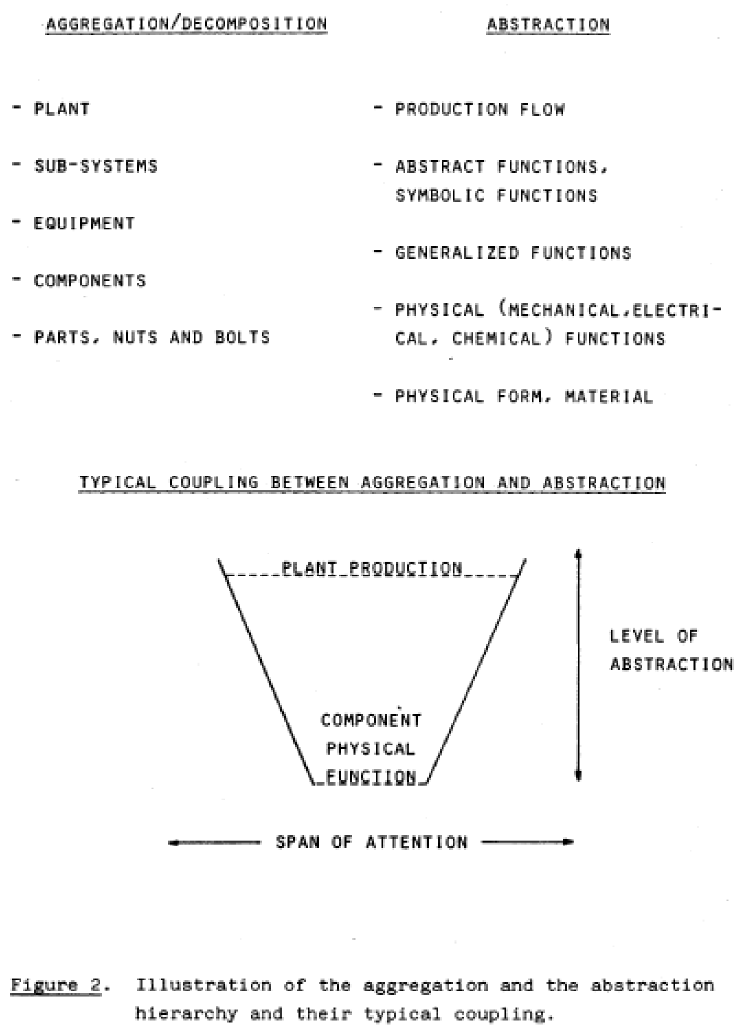
3.4.2.5 Extending the AH: Reasons-Causes Hierarchy (RCH)

3.4.2.5.1 RCH for Environment

As mentioned before, while dealing with human knowing and acting, the designer adopts two stances — the intentional stance and the design stance. The design stance (emphasizing a technical-rational perspective) allows for humans to be treated as components of systems; whereas, the intentional stance (emphasizing the actor-based perspective) allows for the treatment of humans in such a manner that the designers can share their perspective and understand how these humans know and act in situations.

Along with these two stances, the differences between operators and users were also highlighted. Operators act in order to ensure that the system functions correctly; thus, typically, their intentions are subjugated to the manner in which the system was designed and ensures correct functioning. In contrast to the operators, users align their intentions with the system, in order to ensure their own outcomes. The intentions of the users are not subjugated by the systems' workings and therefore their interests remain paramount. Further, in terms of system functioning and the association of roles over a period of time, operators and users follow different trajectories. Operators adapt to their work contexts developing shortcuts and workarounds and may acquire a generalized "feel" for the work context. Whereas users adopt and appropriate technologies for their own use and at times modify these technologies significantly.

It is to be highlighted that parts of a system, such as objects, can be *used* for purposes, other than what they were *designed for*. This is only possible if there is the physico-chemical support for it as well the proper context in which a new use is warranted. Therefore, a screwdriver can be used for opening the lid of a tin can because it has the hardness and the shape to act as a lever; thus having the physico-chemical support to allow for that particular activity. At the same time, a screwdriver can also be used as a murder weapon because of its pointed edge that can be used for piercing. In other words, an object *affords* certain properties to an individual based on its properties, the person's intentions and experience, as well as the overall context (see Gibson's approach in this chapter, Section 3.2.2).



AGGREGATION/DECOMPOSITION

- PLANT
- SUB-SYSTEMS
- EQUIPMENT
- COMPONENTS
- PARTS, NUTS AND BOLTS

ABSTRACTION

- PRODUCTION FLOW
- ABSTRACT FUNCTIONS, SYMBOLIC FUNCTIONS
- GENERALIZED FUNCTIONS
- PHYSICAL (MECHANICAL, ELECTRICAL, CHEMICAL) FUNCTIONS
- PHYSICAL FORM, MATERIAL

TYPICAL COUPLING BETWEEN AGGREGATION AND ABSTRACTION

Figure 2. Illustration of the aggregation and the abstraction hierarchy and their typical coupling.

Figure 3.4: Aggregation and abstraction of entities (Rasmussen & Lind, 1981, p. 13, fig. 2)

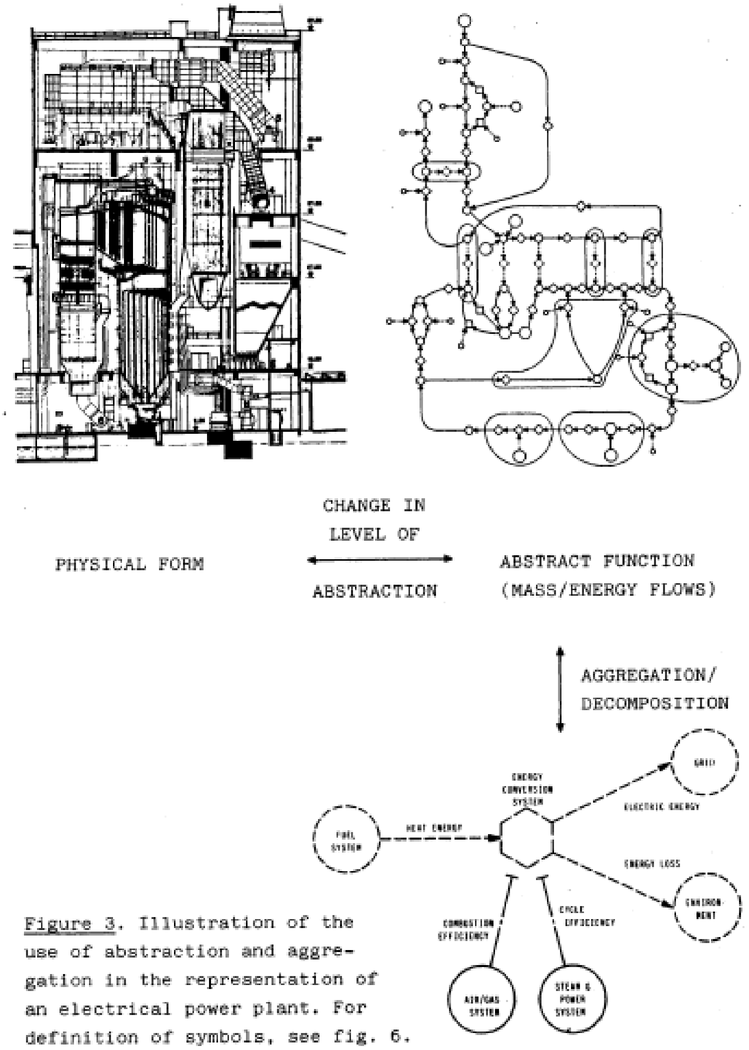


Figure 3. Illustration of the use of abstraction and aggregation in the representation of an electrical power plant. For definition of symbols, see fig. 6.

Figure 3.5: Abstraction and aggregation dimensions for structuring a technical system (Rasmussen & Lind, 1979c, p. 14)

In a more substantial case, discussed by Pedersen and Rasmussen (1980), the unanticipated use of an object is highlighted. The authors recount a case of boric acid plant malfunction in Palisades in August, 1973, in which a lever was used as a stepping point:

> "The valve location is such that it was suspected that the valve (hence, the lever) may have been used as a convenient stepping point during construction and early operation of the plant. The people using the valve as a stepping point are assumed to have been occupied by skill-based tasks not involving knowledge of valves and their properties." (Pedersen & Rasmussen, 1980, p.4, case 69)

This example indicates that the lever afforded stepping on for one group of people who were ignorant about the valve's actual purpose. The context in which the valve was present along with the people involved in the situation led to a novel use of the valve for which it was not designed but was used. From a systemic perspective, this use was not the valve's intended use; therefore, such instances led to faults in the overall system.

The above example highlights three interrelated aspects. First, along with the material form, there is a necessity for highlighting the *use value*[14] (affordances) of the material objects, i.e. how they could be used in certain situations. Towards this end a new layer can be introduced: the use-value layer. Second, this use-value layer should be placed as the lowermost layer in the hierarchy as it presents the level, which may contribute to the malfunction of the system. As the above example shows, malfunctions may be due to the physical form being used in ways not anticipated or desired by the designer initially. In case of the valve, the use-value of the valve in that given situation was the step-on-ability by people emphasizing skill-based knowledge. In case of people who had proper knowledge about the valve's actual function, for them the use-value was different and corresponded to the actual designed function of the valve. Therefore, by being placed at the bottom of the hierarchy, the level of the use-value connects to the upper level of the physical form where the form involves the physical description of the valve. The same physical description can have multiple use-vales depending on the capabilities of the people involved. Thus, improper use of the valve by a certain group of people possessing particular capabilities results in fault of the overall system. As causes for faults propagate upwards in the

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[14] For a broader understanding of the term "values", see Mitcham (2005). The emphasis on use-value as compared to the designed function is similar to the difference between accidental function and proper function from Kroes (2012).

AH, the use-value layer (or affordances layer) is placed at the bottom. Third, along with accounting for possible uses for the material form, a need for conceptualizing the person for whom the physical form has meaning and value is required. The following figure shows the new hierarchy (RCH_E) along with the addition of the new use-value layer.

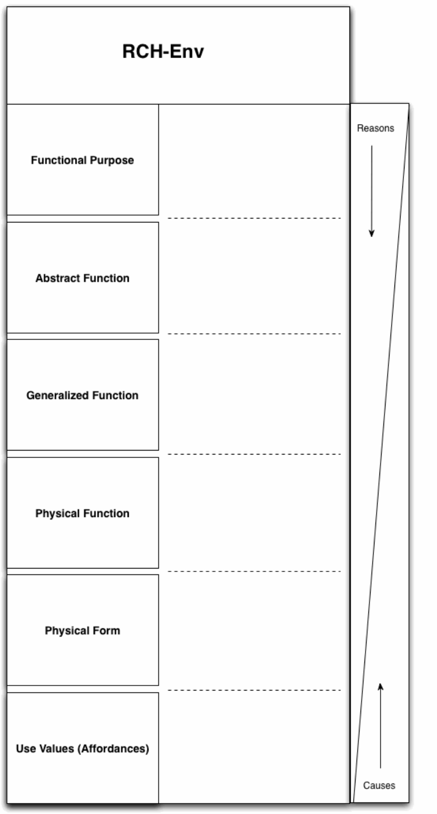

Figure 3.6: RCH for Environment

3.4.2.5.2 RCH for Person

As the above description implies, the presence of use-values of objects is valid only in the presence of a person with relevant capabilities. Therefore, the next step is to provide a model for the person in the technical context. To account for the model of a person, three considerations are necessary. First, the model is to be developed from a design stance with a view towards the overall system. Following from this is the second consideration in which the human is treated as a part of the system and is conceptualized in functional terms. Third, the functional conceptualization must take into account the performance capabilities of humans in order to complement the use-values of physical objects (see Bernstein's views on considering the body together with the performance earlier, Section 3.2.3; also see affordances and use value in Sections 3.2.2 and 3.4.2.5.1).

In order to consider the capabilities of the human, the SRK taxonomy is used. SRK consists of categories of human performance in terms of skills, rules and knowledge. These three categories present analytical differences in human performance on the basis of the various skills required for completing a task, the rules and heuristics involved in that task, and the background knowledge required (Rasmussen, 1983). In the proposed framework, SRK will be used as categories to present human performance. Therefore in order to present the body together with the performance in characterizing the person, a new hierarchy is created. In this hierarchy, a level of human capabilities is added to Rasmussen's functional model of the humans.

In his 1979 paper, for each level of the abstraction hierarchy, Rasmussen (1979) described a corresponding set of models for conceptualizing the human at that particular level. By 1983 (Rasmussen, 1983), the human was depicted in terms of the abstraction hierarchy. This hierarchy for depicting the human is used here to represent the person involved with the technical context. Due to the demands of accounting for the capabilities of humans, Rasmussen's hierarchical representation of the human is extended to incorporate the SRK taxonomy. The SRK taxonomy is used in terms of its division between skill-based, rule-based and knowledge-based categories of understanding human performance. This new layer of SRK is also used to provide a fuller description of the human, accounting for the functional capabilities of action. This layer is placed at the bottom of the hierarchy as any deviation of the performance capabilities would account for the malfunction of the system. For example, if there is an error in recognition or identification, it would constitute as a fault towards the overall system. Therefore, even though the intention of the human is aligned to the systematic goals of correct functioning, the faults may be caused due to performance of the human.

Figure 3.7 shows the AH for a person from Rasmussen's (1983) paper on Skills, Rules and Knowledge categories in human performance. Two major changes have been done to this AH to produce RCH (Figure 3.8). First, the level of capabilities is added as the lowermost level. Second, the labels of the levels have been expanded in light of the theoretical basis of WIDF. For example, in case of the second level of abstract function, information processing is supplemented with psychological and physiological laws. This is because there are many energetic relations involved in the constitution of the person. For example, Kleiber’s law provides the relation between the body mass of an animal and its metabolic rate. Since these laws of energetics can be presented in an abstract set of representations bereft of the physical instantiations, they are placed in the second level of abstract function (see description of abstract function in Rasmussen, 1979). Similarly, the labels of the other levels have also been expanded. These expansions are within the categories of models described by Rasmussen (1979) for each level of the hierarchy. Therefore, for each level only the type of entities that are permissible have been placed there. The discussion of the body enables a way of addressing the traditional physical ergonomics in relation to CWA. Traditional physical ergonomics presents a variety of methods, such as Rapid Entire Body Assessment (REBA; Hignett & McAtamney, 2007), Rapid Upper Limb Assessment (RULA; McAtamney & Corlett, 1993). Using these methods with the extended CWA (WIDF) can provide a rounded view, capturing both the cognitive and physical aspects or work, for addressing the human in HFE research.

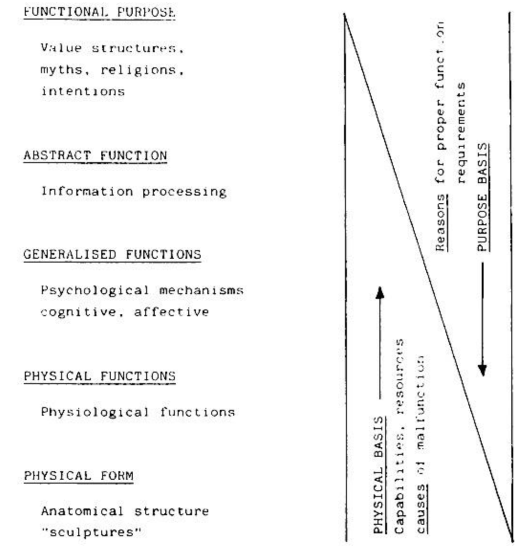

Fig. 4. Models of man also exist at several levels of abstraction. Note that interaction with work environment will require consideration of all levels from physical injuries at bottom to perception of goals and policies at top.

Figure 3.7: Levels of abstraction for a person. Reproduced from Rasmussen (1983, p.283, fig. 4)

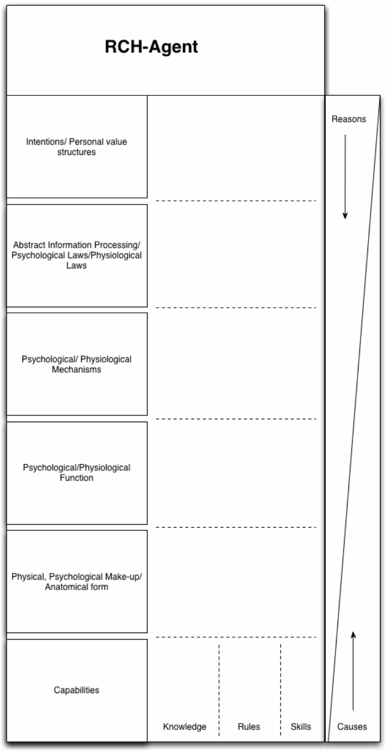

Figure 3.8: RCH for Agent

3.4.2.5.3 RCH for Act

Initially, the first step was to recognize that the physical form level of the AH should be understood in relation to the human. To incorporate this basic insight, models of the context (RCH_E) and the model of the human (RCH_P) were proposed. The figure (Figure 3.9) indicates this basic relationship.

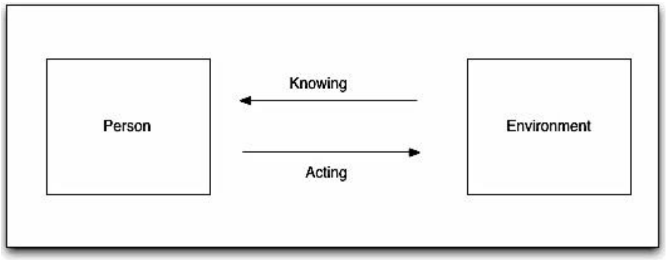

Figure 3.9: Knowing-Acting relationship between person and environment

This figure (Figure 3.9) depicts three major analytic components: the person, the context and the relations between them. Having provided models for the two, the next step is to provide an analytical model for the relation between them. This relation is best characterized as an ongoing process of knowing and acting. As discussed before, knowing and acting are two faces of the same coin (Gibson's approach). Knowing is an activity. Thus, the aim of this model is to capture this relationship (activity). The strategy of modeling will be similar to that of the other two models of RCH_E and RCH_P. Therefore, it will be derived from Rasmussen's AH and will be structured taking into account the design stance of correct functioning. Another requirement from such a model is to ensure the internal consistency of the acts and also to maintain linkages to other hierarchies so as to maintain a holistic consistency. The levels of the proposed hierarchy will be similar to the generic ones used in the previous two hierarchies. Further, it must be reiterated that analytical distinctions and divisions made in this hierarchy are for the purpose of systems design and not in terms of metaphysical distinctions based on the true nature of knowing and acting. Therefore, based on insights derived from Gibson, Bernstein and Blumer, the act is treated as a set of functional entities, at various levels of abstraction, linked together by the concept of correct functioning.

In RCH_A (Figure 3.10), the topmost level comprises of symbolic function or symbolic meaning. Analogous to the topmost level of Rasmussen's hierarchy, this level links the properties of the act in terms of the relation with the overall purpose; in other words, it links the meaning of the act to the overarching matrix of meanings (symbols) of which an act is a part. At this level, symbolism is treated at a level of abstractness that takes into account its generic nature. This level can be depicted in terms of networks of meanings that are vital for the activity to be executed smoothly, in order to account for overall system functioning. The representation at this level consists of a network of symbolic meanings that serve as the basis for the act.

At the next level of abstract function, there is a necessity to represent the entire model of activity in terms of a generic causal network structure. This generic causal network allows for a representation of concepts that are axiomatically true for the realm of activity. The reasons at this level of abstract function provide the reasons for correct functioning to the lower levels. The contents of this level are provided by a consideration of the level of functional meaning. Rasmussen (1979, p. 33) notes: “Psychological models in this domain are typically those of recent cognitive psychology which are based on formal information processing concepts and cybernetic principles”. Information processing activity is to be understood in terms of the overall meaning of the act. This information processing activity [15]depicted at the abstract function levels allows for structuring the act in generic terms using a common language. Therefore, this second level is to be represented in generic terms that are bereft of the physical aspects of embodiment of the acts. Rasmussen notes the following aspects to be considered while addressing the generality of systems design: “Here, the overall function of the system must clearly be described independently of the local physical functions of its elements, since the information content of physical variables and states depends purely upon a set of translation conventions” (Rasmussen, 1979, p. 31). In order to depict this level of abstract functions, the decision ladder (Rasmussen, 1974b) will be employed, as it presents the information processing in abstract terms, as well as captures the shortcuts used by experts. Further, it is to be noted that in the present case, the decision ladder serves as a constraint on the domain. In this particular case, at this level, the

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[15] Bennett and Flach (2011) use the term “Meaning processing” to separate Gibson’s ecological approach from standard information processing psychology. Even though the terms arise from different approaches, at the level of abstract function, both terms can be used to provide completeness. This is because from the perspective of abstract functioning at this level of the engineering approach of WIDF, a demarcation between various meanings of information has not been made. A complete discussion of information from Gibson’s approach as different from the information in information processing psychology is not provided, as it is not the main aim of this thesis. See Gibson, 1966, for a discussion of “information” in ecological approach, in contrast to the standard information processing approach.

decision ladder is used because of its particular support for both novices and experts (in terms of shortcuts). However, if required other models at the same level of abstraction can be used (for details on the permissible models at this level, see Rasmussen, 1979).

At the third level, the models in terms of functional structures prevail. This level lies in the middle of two extreme ends of abstractness and concreteness and therefore has an optimal mix of the two. At this level, there is a consideration of the models in terms of natural language descriptions that can be represented in terms of the functioning of entities and their properties. In order to represent this layer for acts, a description is required in terms of the generic strategies that are required to complete the act. At this level there are generalized representations of behavior to represent the flow conventions. These strategies gain their reasons from the upper level of abstract functions; in turn, they serve as reasons for the level of physical functions below. This level of strategies can be depicted in terms of information flow structures. These information flow structures are block diagrams that display the possible strategies in terms of information processing steps (represented as blocks) and completed information states (represented as circles). Similar to the previous level, the information flow maps for strategies acts as constraints.

At the next level of physical function, the variables and their relations are delimited. Typically, at this level of representation, models of the system are chosen corresponding to the components. Such representations are necessary during design, as they help to coordinate among the various components of the system. Also at this level, there is a growth in the nature of the tangibility of the model; i.e., the models are less abstract than the level above. Therefore, in order to represent this level for acts, there should be some consideration in terms of the commonsense division of the tasks and a representation that connects the overall task in terms of its components. In accordance with this requirement, at this level, a Hierarchical Task Analysis (HTA) will be conducted. A HTA allows for a breakdown of the tasks in terms of their systemic components (Shepard, 2001). Thus, the HTA allows for an act to be presented in terms of its components for the purpose of systems design. Similar to the decision ladder for information processing and information flow maps for strategies analysis, the HTA acts as a set of additional constraint. In each of the above three levels, the entities of the levels are explored further by additional analysis that acts as a set of constraints. However, in selecting these steps for further constraints, two aspects must be noted. Namely, the type of analysis and the models it produces must be in accordance with the type of models in the original categories, presented by Rasmussen (1979). This is because the choice of analysis based on the permissible set of models allows for adherence to the theoretical assumptions of the framework. Thus, the results obtained from the additional analysis will not present ambiguity in terms of the elicited design requirements.

At the fifth level, the physical aspects of the act are considered. The act comprises of the patterns of the behavior in relation to each other. At this level, they are typically depicted in terms of linear chains of activity and descriptions based on movements of the body, bereft of the functional purpose of which they are a part. Thus, at this level the ongoing processes can be considered, for all practical purposes, largely automatic. For example, walking consists of a pattern of activity, which implies taking one step at a time alternately with each leg, but this act of walking largely proceeds automatically. However, it must be highlighted that these linear patterns of behavior are supported by combinations of synergies of muscular activities and background processes in the body and the environment (for e.g. see Bernstein, 1996; also Rosenbaum, 1991, Ch.5). Thus, at the lowermost physical level, the act is considered in terms of the background processes and automatic activities proceeding with minimal or no control.

The above description of acts is patterned along the traditional AH, thus, providing for an internal consistency of the various layers. As described before (Blumer's approach, Section 3.2.4), acts are relations between the person and the environment, which are shaped in the overall interactional context. This context also has other people present who may misinterpret the act, mistaking a blink of an eye for a wink. Or they may provide an interpretation that is novel. Therefore, acts should be seen in relation to the overall context and also in terms of the models of the humans present in the situation. Therefore, a wink will only be understood as a wink if the other person has the capability to grasp the meaning of the wink based on the context, i.e., the person should have relevant knowledge. The misinterpretation of acts implies a need for a level of interpreted value of the acts that links the hierarchy of acts to the other two hierarchies. Since misinterpreting acts may cause the act to be understood differently from what it was intended for, such a scenario may prove as the basis of faults in the overall system. Thus, this new layer is placed as the bottom-most level. The hierarchy of acts (RCH_A) shown below incorporates such a layer.

3.4.2.6 Extending RCH with Aggregation/Decomposition - RCAH

After the AH has been extended to RCH, the RCH (abstraction) has to be coupled to aggregation/decomposition to account for a complete understanding of the work context. The first hierarchy for the environment ($RCAH_E$) is coupled with the aggregation/decomposition of the technical context. Therefore, in a step analogous to Rasmussen and Lind (1981), the RCH is extended to Reasons-Causes-Aggregation Hierarchy (RCAH). RCAH accounts for both aggregation and abstraction and can be depicted in the following manner.

After the RCAH for environment, the RCAH for acts is in order. Acts can be decomposed into *overt* and *covert*. Overt acts are openly conducted; whereas, covert acts are not openly displayed. Such a distinction between overt and covert is made in order to account for the individual. In the case of groups and teams as well as large organizations, the decomposition could be made in terms of team activity, joint activity of dyads or triads, as well as individual activity. Depending on the nature of the research area and the discretion of the designer the proper choice of the decomposition is created.

In accounting for aggregation/decomposition at the level of people, similar to the acts, distinctions could be made in terms of teams, such as dyads and triads, as well as individual roles. However, since the scope of the thesis is not on teams, currently the decomposition is in terms of the roles of the members involved in the work context.

At this juncture, it is necessary to reiterate that the choice of decomposition depends on the research area under consideration along with the designer’s discretion. The above three RCAH (abstraction-decomposition/aggregation) knowledge structures taken together comprise the framework as a frame of reference for orienting the designers and providing them with a systematic method to elicit design requirements. The RCAH structures are also linked with the main themes of this thesis. The theme of embodiment was highlighted by providing the role of the body in conjunction with the performance ($RCAH_P$). The theme of embeddedness was addressed by providing a conceptualization of the environment ($RCAH_E$). Finally, there is a need for addressing situated knowing and acting by highlighting the main constituents of purposeful activity and its relation to RCAH structures. Therefore, the next step is to address RCAH structures together and show how they are linked together in order to support situatedness and also to present a unified understanding of the framework.

3.4.2.7 Conceptualizing knowing and acting in situations

A central idea in WIDF is to treat interface design as a systemic concept for supporting human knowing and acting in various situations. Situations comprise of goal-directed behavior of people in their surrounding contexts. From a systems design perspective, any design should not only be focused on instances, but must also take into account a multitude of possibilities. In other words, the design should be focused on generic categories. To account for purposeful activity in terms of generic categories we turn to the Dramatistic pentad of the literary theorist Kenneth Burke. The pentad, conceptualized as a grammar for understanding motives[16], is used to answer the question: “What is involved, when we say what people are doing and why they are doing it?” (Burke, 1969, p. xv).

Since WIDF is concerned with the design of systems in which people are involved in purposeful behavior, the pentad presents a viable tool for the basis for development of the WIDF. However, similar to the approach taken before, WIDF will not be a direct application of the pentad but will use concepts presented by the pentad. In terms of the scope of this thesis, it is important to note that the pentad is treated as a *grammar* of motives; i.e., regardless of the actual content, the manner in which the syntax and morphology is used to demonstrate particular instances. Therefore, its categories can be used in a generative manner in order to assess and categorize the elements of goal-directed situations. Further, there is a necessity for addressing all five terms of the pentad for giving *any* complete answer to situations. Therefore, in the section below, the five terms are used to develop WIDF.

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[16] For Burke, motives are shorthand of situations (Burke, 1954).

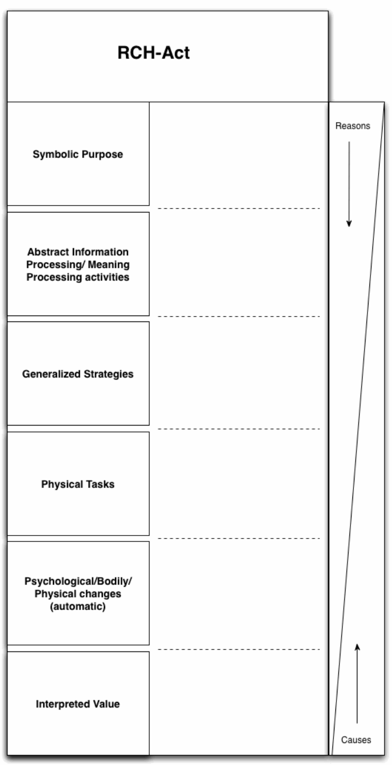

Figure 3.10: RCH for the relationship of knowing and acting (RCH-Act)

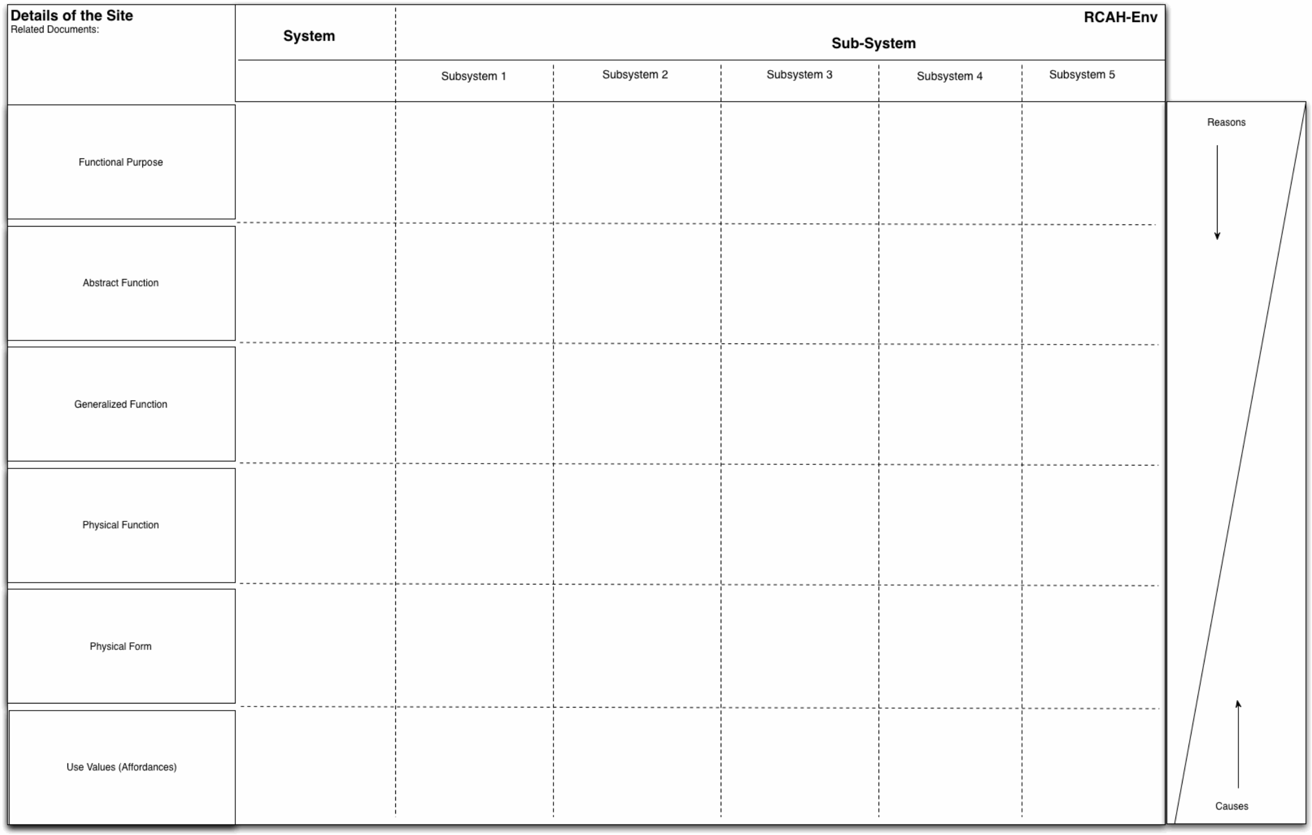

Figure 3.11: RCAH for environment. The abstraction is in terms of the function-structure linkage and the decomposition is in terms of system-subsystem. Overall view, details have been presented in RCH-Acts

3.4.2.7.1 Kenneth Burke's approach – grammar of situations

To understand the universality of Burke’s pentad, a slight foray is needed into the world of Kenneth Burke and his treatment of human knowing and acting. Kenneth Burke is recognized as a major figure in the field of literary theory. Over a period of time, beginning with the analysis of literature, Burke derived a framework for understanding goal-oriented behavior: dramatism (the name retains its implication of the world of literary theory). Apart from the pentad, Burke’s agenda is quite large — he attempts to provide not only a method for understanding literature and rhetoric but also treating it as equipment for living. Therefore, in his larger body of writings, there are a profusion of terms that he has used to develop his approach to dramatism (for e.g., scapegoating, victamage, consubstantiation, among others; see Rueckert, 1963, for broader discussion of Burke’s approach). Though Burke has addressed human living more generically, his style is largely idiosyncratic and has not made a lot of inroads into the traditional fields which lay claims to addressing human knowing and acting, such as psychology and sociology (Kenny, 2008). This is in spite of the fact that Burke’s article on dramatism is labeled under the heading of interaction in the *International Encyclopedia of Social Sciences* (Burke, 1968); or that it directly follows the article on symbolic interactionism in the same book. Sociologists, in general, have been limiting in their treatment of Burke (Overington, 1977a, 1977b).

In the field of literary theory and communication studies, where Burke continues to remain influential, discussions have ranged from dramatism as an ontological or epistemological concept (Brock 2009; Brock et al., 2009) to the use of the pentad to analyze texts and situations, as well as to understand the motives of the actors in the situation, among other uses (Blakesley, 2002). Further, there remains an ongoing debate about how Burke addressed the pentad, as well as whether the pentad should actually be a hexad rather than a pentad (Anderson & Althouse, 2010; Crable, 2000). These discussions still remain an open debate among Burkean scholars.

In contrast to these multitudes of debates, the present thesis takes into account the constituents of the pentad and its claims of universality to account for motivated behavior in situations. To this effect, three questions are to be answered. First, is Burke’s pentad suitably universal? Second, is the theoretical background from which the pentad has evolved suitable for use in this thesis, i.e., based on the theoretical assumptions espoused in this framework? Third, if applicable on the basis of the above two questions, in what manner can Burke's pentad be used in this thesis?

To begin answering these questions the first insight about the pentad and Burke's dramatism is provided by the sociologist Overington (1977a, p.132): "In principle, dramatism is a method that is applicable by anyone trained in its usage, and it should be allowed to stand or fall as an analytic methodology quite independent of the substantive conclusions about human conduct that Burke draws from his own usage of the method." For the purpose of the thesis, the important aspect is the consideration of the terms and their analytic consideration. For understanding the pentad, it is important to understand its constituents (Burke, 1969, p. xv):

> "We shall use five terms as generating principle of our investigation. They are: Act, Scene, Agent, Agency, Purpose. In a rounded statement about motives, you must have some word that names the *act* (names what took place, in thought or deed), and another that names the *scene* (the background of the act, the situation in which it occurred); also, you must indicate what person or kind of person (*agent*) performed the act, what means or instruments he used (*agency*), and the *purpose*. Men may violently disagree about the purposes behind a given act, or about the character of the person who did it, or how he did it, or in what kind of situation he acted; or they may even insist upon totally different words to name the act itself. But be that as it may, any complete statement about motives will offer *some kind of* answers to these five questions: what was done (act), when or where it was done (scene), who did it (agent), how he did it (agency), and why (purpose)."

Burke's dramatistic pentad contains five terms: scene, act, agency, agent and purpose. These terms, in themselves, are not new as they can be traced to the medieval Latin hexameter as well as to the Greek philosopher Aristotle. Further, these terms could also be considered similar to the "Journalistic Ws" of — who, what, and where, among others (Burke, 1978). In spite of sharing a common background, two aspects separate Burke's pentad with these other systems of accounting for goal-directed behavior. First, Burke stresses on dramatism, as he views language "primarily as a mode of *action* rather than of *knowledge*" (Burke, 1978, p. 330, emphasis in original). Though he also stresses that these two aspects cannot be treated as mutually exclusive. Second, Burke's emphasis on using the pentad is that, unlike Aristotle's list which tells what to *say*, Burke's list tells what to *ask* of a situation. Finally, along with the terms themselves, Burke stresses the ratios of the terms (taken two at a time)[17]. Thus, the above discussion shows that the terms Burke deals with are sufficiently generic and thus worthwhile for addressing purposeful behavior in terms of a small number of categories.

After addressing the first question, we turn to the theoretical assumptions behind Burke's dramatistic pentad. Burke rests his notion of the pentad and dramatism on the notion of action. His primary idea is to treat man as a "symbol-using, symbol-making and symbol-misusing" (Burke, 1964, p. 495). By using language and the use of the negative (i.e., what something is not), humans are able to discuss advanced concepts in terms of the symbolism of the negative. Further, this use of language makes the human different from other animals in terms of using words about words. Thus, humans are able to make vast symbolic structures based on language.

Along with language, humans have a tendency to systematize and search for a sense of order; in other words, humans have a tendency to search for a "proper" way of doing or naming things. These tendencies form the basis of Burke's broader approach to human relations as well as the pentad. It is to be noticed that the notion of the symbolic interchange is also a key idea of symbolic interactionism as well as Rasmussen's approach. Further, a key assumption of this thesis is that humans are symbol-making and symbol-manipulating creatures that are best understood in the matrix of symbolic interchange and activity. Thus, Burke shares the theoretical assumptions adopted in this thesis and allows for a coherent and systematic framework of WIDF. However, it must be stressed that unlike Burke, the focus of this thesis is on systems design. Therefore, even though Burke's pentad and its terms are used, they are not used in the same manner as other literary theorists. Such a move is made in accordance with the sociologist Overington's (1977a; also see, Overington, 1977b) premise of treating the pentad strictly as a cluster of terms as an analytical methodology (quoted above).

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[17] Burke also stresses the notion of "circumferences" to emphasize the overall background that serves all of human relations. This overarching agenda is not used in this thesis and this concept will not be developed any further. (Burke, 1978, p.330)

3.4.2.8 Conceptualizing the terms of the pentad for WIDF

Having shown the applicability of Burke's framework to this thesis, the final step is to account for all the terms and make them applicable for systems design. As a reminder, Burke's pentad consists of five terms: scene, act, agent, agency and purposes. Till now, three terms have been addressed in terms of RCAH hierarchies: scene (RCAH_E), agent (RCAH_P), and act (RCAH_A).

The three hierarchies also account for purpose; however, they do so in a manner that highlights the different aspects of purpose in the entire system. Since the RCAH_E has evolved from the standard AH, which was a representation of a technical system, it has the notion of designed purpose embedded it. From the perspective of RCAH_E, modern work contexts do not appear out of nowhere but are the result of a multitude of design and policy choices over a course of time. In case of people, the topmost layer of the RCAH_P accounts for their intentions. Finally, in case of acts, $\text{RCAH}_{A,}$ the meaning of purpose lies midway between the other two hierarchies. As situations unfold, contingencies, avenues and novel lines of activity appear. People participating in situations often find themselves getting involved in the unfolding of events. As such, there may be new goals that were not anticipated by the actors initially but that emerge from the process of activity. For example, consider the following scenario: a person is going to his office on a cold icy morning to give a presentation. On the way, he sees a person, who is walking his dog, slip and fall. Seeing no one else in the vicinity, the first man stops the car and tries to help the other person. Noticing the bump on the fallen person's head the first man calls the emergency services and waits till they arrive. When the ambulance comes, the person who is hurt asks the good Samaritan to take his dog and leave it at his home, which is two streets from their current position. The story goes on; however, it is enough to demonstrate that events often acquire their own momentum as they unfold. Thus, the symbolic purpose of acts can be distinguished from the intentions of the people and the functional purpose of the context. However, acts are always to be considered in relation to people and the context and thus the hierarchy of acts should be addressed in relation to the other two hierarchies under consideration.

After accounting for purposes, the final aspect of the pentad consists of accounting for agency. Burke's use of agency is interpreted as what means or instruments are employed by the agents. In the case of instruments, accounting for instruments can take place in two ways. First, instruments can be considered as a part of the context ($RCAH_E$) when not in use. However, when they are used they act to extend the capabilities of the agent. It is a general fact of experience that when one holds a pen to write, the tip of the pen feels to be on the paper[18]. The hand-pen interface feels transparent; i.e., the interface recedes to the back of the awareness. However, when the attention is shifted, the link between the hand and the pen emerges into awareness. Therefore, in the case of the instrument being used, it becomes a part of the body and adds to the person's capabilities. Thus, between the $RCAH_E$ and $RCAH_P$, the notion of agency is addressed. Depending on the work domain under consideration, the designer has the flexibility to model the instrument as part of the person or the environment. A second manner in which agency is employed in everyday work contexts is in terms of a person or a body of people who act on behalf of other people so as to conduct any transaction. In this case, the concept of agency is captured by the hierarchy for people ($RCAH_P$). By accounting for all the terms, the above description concludes the discussion of the categories of the pentad.

A second important aspect of Burke's pentad is the ratio of the two terms taken together. In terms of WIDF, the ratio between terms helps to minimize and regulate the uses of the terms. For example, in the case of the scene-agent ratio, the $RCAH_E$ and $RCAH_P$ are taken together. In the case of $RCAH_E$, in the level of physical form and corresponding level of use-value, the objects can ideally have a multitude of use-values. However, when taken in relation with the people involved in the work context, only a few major use-values remain. Similarly, taking the ratio of scene (environment) and acts allows for a further reduction of the interpreted value of objects. Reciprocally, limitations on the use-values imply a reduction in the possibilities of misinterpretation of acts involving those objects. This in turn depends on the capabilities of the people involved. This reduction of entities, when the hierarchies are considered together, is based on the demands of the work domain as well as the discretion of the designer in gathering requirements. The three hierarchies are mutually constraining of each other and when taken in ratios considering two concepts at a time, the extraneous possibilities are effectively curtailed. Thus, this ensures that the hierarchies have internal consistency along with external linkages to the other hierarchies. Thus, WIDF consists of the three hierarchies taken together to account for

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[18] This insight has been discussed by phenomenologists (for e.g. Ihde, 1990), ecological psychologists (for e.g. Gibson, 1979), and anthropologists (for e.g. Bateson, 1972), among others.

the context, acts and people. This description of the hierarchies in terms of the pentad allows for the characterization of purposeful work situations and providing requirements for interface design. This formulation of the three hierarchies for addressing situated behavior concludes the second step of WIDF.

3.4.2.9 WIDF and CWA

The extended CWA (WIDF) may seem different in structure from the traditional CWA. However, this difference is superficial as the extended CWA uses the anatomy of the AH to extend the traditional phases of CWA. For example, the first phase of Work Domain Analysis (WDA), pertaining to the environment, is also captured by RCH_E in the extended CWA. The phases addressing the decision-making and strategies have been addressed in RCH_A along with other analysis for presenting a fuller understanding of activities. Finally, the SRK in the fifth phase of the traditional CWA has been addressed in the RCH_P for a detailed understanding of the body and performance in everyday activities. The fourth phase of the traditional CWA addresses the social and organizational dimensions of systems. Currently, this dimension is out of the scope of the extended CWA and will be addressed later. This limitation will be discussed in the conclusion to this thesis. A second manner in which WIDF extends CWA is by highlighting the hidden dimension of engineering epistemology (reasons and causes in the development of the abstraction hierarchy). By highlighting this dimension allows for explicitly extending the new hierarchies to produce new configurations for addressing novel technologies. Thus, even though structures of WIDF may look different superficially, they are built on and extend the basic principles of CWA. Therefore, this thesis adds to the above literature on CWA research by extending CWA in terms of fundamental principles.

3.4.2.10 A short note on the nomenclature

WIDF is classified as a design framework due to two main reasons. First, WIDF is a design framework because it is constructed by taking into account the design theoretic concepts of function-structure linkage, correct functioning and malfunction (design used as a form of knowledge). Second, it is a design framework as it takes into account the actor-based perspective along with the technical-rational perspective for systems modeling and design. The typical view adopted in the technical rational approach is the division between analysis and design. In other words, first the requirements are generated in the analysis phase and then the design process is conducted (for e.g. CWA for analysis and EID for design). In contrast, in the actor-based approach, the division between analysis and design is not as clearly demarcated as in the technical rational approach; analysis and design are intricately entwined. The designer plays an integral role in both the analysis and design. Currently, WIDF incorporates both the technical-rational and actor-based approaches; there is no strict demarcation between analysis and design. Step 1 allows for the designer to be interpretatively involved with the subject matter under consideration, whereas Step 2 allows the designer for providing models based on Step 1. The designer is intricately involved in both the steps and the tacit knowledge of the designer allows for a fluid exchange between the two steps. Further, the hierarchies developed in WIDF will be extended later for the actual *process* of design (i.e., akin to EID; currently, this aspect is out of the scope of this thesis). Taking these two aspects into account, WIDF is labeled as a design framework.

3.5 WIDF - Summary

Conducting WIDF requires two steps. In the first, the designer gains a broad understanding of the work domain through a qualitative mode of understanding. Based on the data gained from the first step, in the second step the designer builds the models using the three hierarchies (RCAHs). Roughly speaking, the first step corresponds to acquiring an interpretive insight into the inner processes comprising the work contexts; whereas, the second step corresponds to producing engineering knowledge structures based on the data obtained in the first step.

The first step requires the designer to adopt an intentional stance towards the actors and their activity. In treating people as agents, the aim is to address the work context through an interpretative understanding in order to achieve an “intimate familiarity” with the subject matter. In taking this approach, the context is envisioned in terms of a multitude of interacting and mutually entangled processes. Thus, the work activity is not only conducted by the humans; but more specifically, by humans *immersed* in the work context. In this context, the workers act towards objects as well as towards each other in terms of the generic orientation they have towards their surroundings. Therefore, the important aspect to be noted is that a detailed study of situated activity is required. This depiction of activity in terms of processes allows for an accounting of meanings and how these meanings change over a course of time as events unfold.

During this stage the accounting of challenges, negotiations and ambiguities found in work contexts are important as it provides an understanding of the overall matrix of interaction in which the work activity occurs. Accounting for this overall matrix of interaction in terms of sustained ethnographic enquiry is also important, as it touches upon the variety of meanings and work processes, including the emotional circumstances of people. The stress and struggle that workers undergo during work is important for understanding the work situation as it often has an indirect influence on the activity and design of interfaces for the work contexts. These various aspects of everyday work lives need to be understood, even if they are not accounted for directly in engineering frameworks. This first step is also required as it gives the designer an insight into the symbolic universe of the work context. Ultimately, the designer has to design for the actors in work situations. For the design to be useful, it becomes an imperative that the designers share the actor's symbolic universe. Thus, the first step is conducted by the traditional process of ethnographic enquiry with the theoretical approach of symbolic interactionism. A processual approach is used to organize and assimilate the data and demonstrate the myriad ways in which the interacting events unfold.

In the second step, using data obtained from the first step, the hierarchies are used for eliciting design requirements. In using the three hierarchies along with their decomposition elements the designer uses the design stance to envision the various hierarchies as parts of the overall work system. Further, the structure of the hierarchy allows for concepts of correct functioning and the "logic of contrivance" (reasons and causes), to allow for eliciting design variables that the designer can use in the design process. Thus along with the processual approach in step 1, the engineering knowledge structures in step 2 together present a unified understanding of the work context in order to elicit design requirements. Even though these two steps are provided for eliciting design requirements, it is possible to improve upon the set of gleaned requirements by adopting other methods of analysis to either improve the existing requirements or gather new requirements not currently addressed by the proposed models. For example, this is possible for the concept of "sociality". WIDF treats "sociality" as an inherent aspect of systems design. Therefore, the ethnographic approach is a part of step 1 of WIDF. Further, in order to explicitly model phenomena that lie under the label of interpersonal behavior, it is possible to explicitly model it in step 2 of WIDF. These new models for particular activities or phenomenon will act as constraints, thus they will help to clarify or add to the requirements already obtained. However, it is to be noted that in order to get a coherent outcome, the choice of these new methods should be such that they share common theoretical assumptions with WIDF. Also, when applying new methods of analysis along with WIDF, it should be ensured that they share meta-theoretical similarities with WIDF. This aspect should be ensured to avoid conflicting requirements.

3.6 Conclusion

The main aim of this chapter was to introduce the proposed framework WIDF. This framework allows for eliciting design requirements for embodied, embedded and situated aspects of human knowing and acting. The theoretical approach for this framework derives from the engineers J. Rasmussen and K. Vicente, psychologist J.J. Gibson, sociologist H. Blumer and motor control (activity) theorist N. Bernstein. All these theorists have addressed human knowing and acting and highlight various dimensions, which are used to develop this framework. Even though this thesis derives from these theorists, no attempts have been made at any sort of theoretical synthesis; neither is WIDF a direct application of any of these theories. Based on the generalized insight gained from knowing and acting in work contexts, the framework WIDF is constructed.

WIDF consists of two steps. In the first step, an ethnographic approach is taken to account for human knowing and acting in work situations. The ethnographic approach emphasizes an interpretive understanding to glean the generic processes related to knowing and acting. The processual approach is necessary in order to account for the changes in meanings and orientation that people have towards their work contexts. The ethnographic approach is also broad in terms of addressing the various aspects of human lived experience, which affect design indirectly but may not be completely accounted for in engineering design frameworks. This first step is also important as it allows for accounting of the large-scale matrix of meaning in which the human activity exists. It is to be recalled that the interface design is a systemic concept; therefore, understanding this large-scale symbolic matrix is important in order to design for the actors and their activity under consideration. The second step in the framework models the data using three hierarchies (RCAHs). The structure of the RCAHs allows for eliciting the design requirements.

The aim of this thesis is to extend CWA in order to present an engineering knowledge framework to design for human knowing and acting. Due to the multitude of aspects from which human knowing and acting can be addressed, the scope of the thesis is specifically limited to the individuals in terms of accounting for systems design; therefore notions of teams, organizations, or political groups are left out at this juncture. Further, a variety of methods and design tools already exist in HFE and HCI for the design of information systems. Given the background assumptions and scope of the methods and frameworks, a designer can also use these additional approaches along with the proposed framework to elicit out further requirements or improve the ones that are already acquired. WIDF primarily extends CWA but does so in a manner by probing its fundamental assumptions. Having shown how WIDF extends CWA, the next step is to show how they can be used for gathering requirements in the field of nanotechnology. In this thesis, three sites are chosen corresponding to devices (Ch. 4); robotics (Ch. 6); and materials (Ch. 8) in nanotechnology. In all three areas, WIDF is compared to CWA. Due to its structure, in all three cases, WIDF generates more number of requirements than CWA.

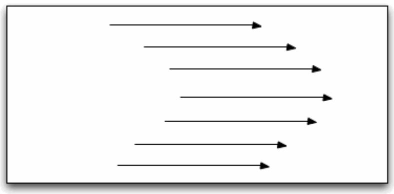
Chapter 4: Site 1—Devices (Ethnographic Study)

4.1.1 Introduction

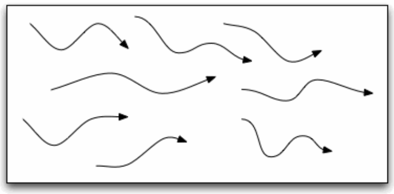
The aim of this chapter is to present an ethnography of Lab-on-a-chip (LOC) technology in micro- and nanofluidics. This chapter serves as the first step in WIDF and provides the basis of a holistic understanding of work conducted in these settings for devices. The main goal of the lab, in which this ethnographic study was conducted, was to gain a fundamental understanding of micro- and nanofluidics; as well as develop LOC technology for biological, chemical and biomedical applications. Soft lithography techniques (described below) were used for the fabrication of chips to ensure rapid prototyping for testing research ideas. In the following account, the fabrication and testing of research chips will be developed in detail, as they were common to the research projects underway in this lab. The primary goal is to provide a generalized account of the ways in which researchers fabricate the chips and later test them. Once these chips were ensured to function correctly, they were used to gather data for the specific research projects.

4.1.2 Backdrop of fluidics research at the small scale

Fluidics as a research area studies the flow characteristics of a fluid, in order to be used for operating control systems. In micro- and nanotechnology, precise control and manipulation of fluids are required for fluid flow through small capillaries. The fluids flowing through these capillaries can be manipulated; i.e., they can be mixed, separated or processed. Micro- and nanofluidics is an area of research dealing with fluids at the smaller scale. It is a multidisciplinary endeavor comprising multitude of groups ranging from physicists to engineers. In order to study fluid flow at the smaller scale, researchers in micro- and nanofluidics build devices that have channels at the scale of microns through which fluid flows can be regulated; thus, being used for various purposes such as separating cells from their surrounding medium. Researchers in micro- and nanofluidics think of fluid flow in these tubules as analogous to electron flow in electrical circuits. This analogy often allows them to successfully create new devices that blur the boundary between these two domains. At the micro- and nanolevel, fluids behave differently than at the macrolevel. Specifically, the fluid at this level demonstrates laminar flow rather than turbulent flow.



Laminar Flow



Turbulent Flow

Figure 4.1: Top panel shows a cross-section of laminar flow; Bottom panel shows a cross-section of turbulent flow

Figure 4.1 indicates that in turbulent flow, some regions of the fluid move faster than the others, resulting in a flow that is marked with differences in velocity. In contrast to the turbulent flow, in laminar flow, the different layers of the fluid tend to slide smoothly over the others. Thus at the smaller scales, laminar flow presents a marked advantage. For example, the smooth flow allows for identification and/or separation of biological cells from the surrounding medium. Further, fluids at the droplet level can be mixed together to design new materials that could be used in food, beverages and cosmetics. For example, in the area of cosmetics, a French company Capsum has used microfludic technology (Lipidots nanovector technology) from CEA-Leti, a French research institute, to produce cosmetics at a commercial scale (Capsum, 2014; Nichol, 2013). Lipidots nanovector technology was developed for medical applications. In this technology, the fluorescent imaging drugs are encapsulated in droplets of oil, for delivery to specific cells in the body. Encapsulating active drugs in a fluid like oil ensures the immiscibility with the surrounding medium, as well as allowing for providing a precise amount of drugs to be provided to specific target cells in the body. Capsum has used the lipidots nanovector technology for proper control of fluids to produce biodegradable nano-emulsions that are free from inorganic particles. Therefore, it presents an improved homogeneous product for lotions and creams with improved texture quality. Lipidots nanovector technology is one of the many nano-related technologies that are rapidly being commercialized due to the marked advantages they present in relation to the currently existing technologies.

The technology behind the present LOC devices hails from early microfluidic devices developed for the analysis of biomolecules, biodefence and microelectronics (Whitesides, 2006). Later in the 1980s, LOCs were developed for the analysis of aqueous solutions. These early technologies were fabricated using microelectronics that required expensive techniques in terms of time and facilities. These devices provided a major advantage in terms of chemical inertness and high quality of end product. However, due to the time- and location-intensive preparation, the technology for developing these devices proved cumbersome for applications that require rapid evaluation of prototypes. A new method of fabricating microfluidic devices was introduced by George Whitesides and colleagues using soft lithography techniques. This method has acquired widespread usage among labs that require rapid prototyping and testing of chips (Kim et al., 2008; Tang & Whitesides, 2009).

In the research lab where the study was conducted, multiple research projects, using soft lithography techniques, related to small-scale fluidics were underway. Soft lithography is a family of techniques by which structures can be fabricated or replicated using elastomeric polymers. These polymers, such as Polydimethylsiloxane (PDMS), displaying the property of elasticity, can be converted into a stamp or mold for developing micro or nanostructures. PDMS was also used as a material for fabrication in the lab in which this study was conducted. Apart from the reduction in time for prototyping and the reduction in costs, the use of PDMS as a material has certain advantages in terms of its permeability, electrical and mechanical properties, among others. PDMS is thermally insulating and is stable up to 300 deg.C and therefore can be used for applications that require heated solutions. PDMS has insulating properties, allowing it to support embedded electronic circuits. It is generally inert and unreactive towards most reagents, thus allowing for its use with a variety of fluids. PDMS is also optically advantageous for use with microscopes as it is clear and see-through after becoming a solid. Further, due to its non-toxic nature, it can be used for biological applications such as mammalian cell growth (Tang & Whitesides, 2009). Apart from these marked advantages, PDMS also displays certain drawbacks. At times PDMS presents incompatibility with certain fluids, i.e., it has a tendency to swell or react adversely with certain organic chemicals (van Dam, 2006, Ch. 3). Despite these challenges, PDMS is viable material for research in small-scale fluidics because of its rapid prototyping capabilities and lower cost.

Along with using PDMS as a cost effective material for prototyping, fluidics labs also reduce the overall cost of research by conducting research in normal lab facilities rather than in “clean room facilities”. Clean room facilities are environments used for scientific research with low levels of contaminations and a controlled amount of pollutants such as dust. To work in a clean room facility, researchers often wear a clean room suit to avoid dust and contamination. Clean room facilities are often mandatory for research in areas such as semiconductors. Typically, the price of operating and using a clean room is quite high. As an example, the clean room facility in the G2N lab in the University of Waterloo has an access rate of CAD$ 3200 for external users and CAD$ 1600 for academic users per term (G2N, 2014). Since the prototyping of devices in small-scale fluidics is possible without the stringent requirements of clean room facilities, researchers often conduct their research in normal lab facilities that are still highly clean.

4.1.3 Laboratory Setup

In order to understand the activities involved in making LOC devices, the first step requires highlighting the layout of the equipment vis–à–vis the processes of fabrication and testing. The laboratory space was divided into two main regions A (A1, A2) & B (Figure 4.2). Section A constitutes the area where the LOC chips are fabricated and the Section B is where they are tested. The fabrication process dealt with chemicals as well as processes that required certain specialized equipment. This suite of equipment was placed in section A in a manner that facilitated the fabrication process as well as provided adequate safety. Specifically A2 was the place where the chemicals were handled; whereas, A1 was chemical free.

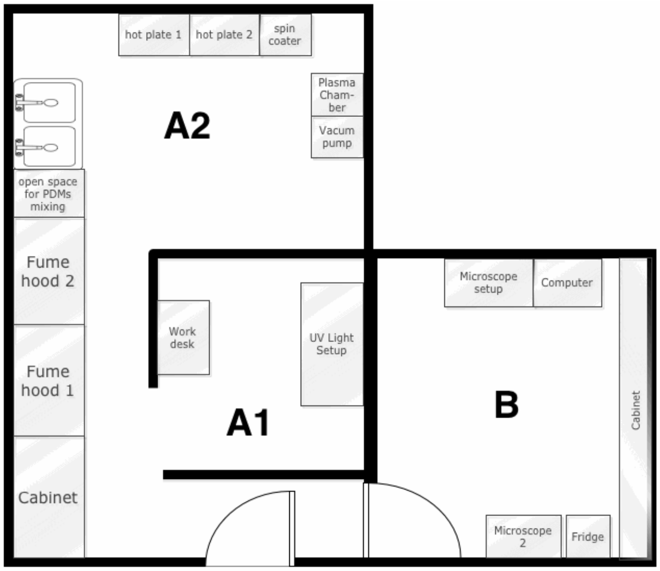


Figure 4.2: Functional setup of the lab where the study was conducted. The lab was divided into Parts A and B. Part A served as the area for fabrication. Part B served for testing the fabricated LOC devices

In general, the area A consists of spin coaters, hot plates, a plasma chamber, a vacuum chamber, a UV exposure system, fume hoods and various glassware and tools. Apart from the above listed equipment, this lab also had other tools and devices not discussed here, as they were not involved in the activity of fabrication. In area A, A1 is a small room that houses a UV exposure system and a small workbench. In area A2, the major chemical processes are conducted in the fume hoods. The other devices are used as the fabrication process progresses. In contrast to the fabrication processes conducted in area A, area B was used to testing the devices earlier fabricated in Area A. In the case of Section B of the lab, chemicals were not present. The finished devices were tested in Section B using the microscope, pressure controllers and computer software for recording data. This separation between the lab sections provided adequate safety and facilitated the research activity.

4.1.4 Details of the Fieldwork

In site 1 the primary procedure adopted was observations coupled with informal discussions. Due to the nature of the work in this domain, during the phase involving data recording, there was a fallow time for researchers between two data recording. This fallow time proved excellent for discussion and clarification of the work being conducted. At this site, the work was observed for about 2.5 months (last week of March to first week of June, 2013). There were six official participants and the overall official time spent in the labs amounted to around 94 hours. Apart from the official logged time a number of hours were spent unofficially in informal conversations and hanging out. Due to the strongly individualized projects in site 1, I followed researchers one at a time and concentrated on one research project at a time. After spending a number of days with one participant, I then cycled to other projects. Apart from the observations, I also got a first-hand understanding of cutting the PDMS. In site 1, after observing a participant for quite some time, I was invited to help him at one instance in handling some material. This enabled me to get a tacit understanding of the bodily expertise required in the process of LOC fabrication. Along with the above observational method, to place the research conducted in Lab 1 from a broader perspective, I supplemented my understanding by informal discussions with other graduate students, in microfluidics, about the nature of their work and microfluidics as a research area. Further, attending seminars and guest lectures in the University of Waterloo provided an overall sense of the research area of LOC technology.

4.1.5 Laboratory Safety

Along with the above setup, safety was a key concern in the lab. Researchers working in the lab had to undergo safety training. Researchers used glasses, gloves, and lab coats to ensure precaution during work hours. There were eye wash stations as well as steps outlined about what was to be done in case of an emergency. While dealing with harmful chemicals, individuals in the process of making LOC devices took utmost care during the fabrication process as well as during the testing process.

Typically, there are considerable safety risks involved in making LOC devices. Working with chemicals required wearing latex gloves all the times. Sometimes, in order to handle dangerous chemicals, an extra pair of gloves was worn by the researchers. Lab coats were also worn at all times in the lab. While working with chemicals, safety glasses were worn. All handling of dangerous chemicals were done under the ventilated fume hood. Further, the lab had eye wash facilities; the area surrounding it was kept free at all times. There were also emergency contact numbers and a phone available in the lab.

4.1.6 LOC Activities

Researchers in LOC technology in microfluidics conduct research by first fabricating the device and then testing it and using it for gathering research data. In the following account, the activities of fabricating and testing will be addressed in detail. A key insight from these observations was that the success of these activities relied on researchers' management of risk and materials, or the "workmanship of risk". Workmanship can be more broadly understood in terms of making as activity. These processes are addressed after the discussion of the activities involved in LOC creation and testing.

4.1.7 Phase 1—Activities involved in chip fabrication

4.1.7.1 Designing initial concept for LOC Devices

The first step of LOC fabrication is governed by an engineering approach in which the whole device is conceptualized. The models are made through Computer Aided Design (CAD) software programs. In this step, the designer envisions the final device in terms of the overall functions and detailed structure. This structural formulation requires knowledge of the laws of fluid dynamics. Using the formula for the Reynolds number, the flow rates and possible pressure across the channel is calculated. The Reynolds number is a dimensionless number that provides an insight into the flow characteristics of a fluid through a channel under various circumstances. Based on the calculations of microvolume flow, the resistance provided by the channel is calculated. These resistances and fluid flow is optimized in terms of the entire device architecture. Microfluidic devices can be made based on different technologies or a mix of those. For example, the devices can be based on a mix of electrical and biological networks embedded in the device. However, in this particular lab, where the study was conducted, most of the researchers focused on "passive devices". In passive devices, researchers change the manner in which the microchannels are configured in the PDMS; as a result, the control of the fluid flow is dependent entirely on the manner in which the microchannels are etched in the device. "Passive devices" can be compared to "active devices"; in "active devices", there are external forces, such as electrical or magnetic forces that can be used to manipulate fluid flow. Therefore, in short, in "passive devices", the researcher controls the overall device functioning by patterning the microchannels.

Once the holistic conception of the device is achieved, the first steps towards fabrication involves “thinking in terms of layers” (Figure 4.3). In order to fabricate the device, all the necessary channel architecture is conceived in terms of their heights. All the features at the same height are conceived to be existing in the same layer. Further, different materials can be deposited layer after layer to make complex devices such as a mix of microfluidics and electronics. Taken together, these layers constitute the device architecture. These layers are printed in high-resolution onto a transparency film to create a photolithography mask. This mask is opaque and allows light to shine through based on definitive patterns. In this process, the UV light transfers the pattern present on the mask to the wafer. These masks can be understood as negatives that allow UV Lights to pass through and thus transfer their pattern onto the device. Since these photomasks are crucial for the device quality, this particular microfluidics lab sent its CAD drawings to an external vendor, located in USA, who provides the photomasks. The turnaround time for this process was typically about five days.

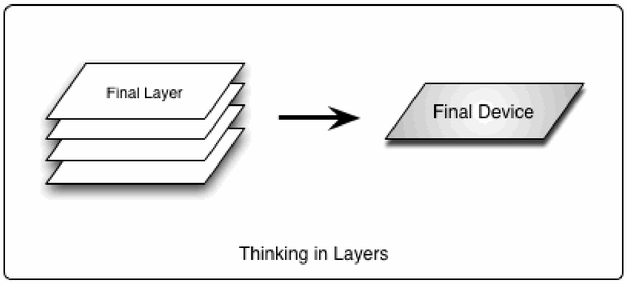


Figure 4.3 : Thinking in Layers for conceptualizing LOC devices

4.1.7.2 Prototyping the Device

After obtaining the photomask, the steps towards prototype development are taken. The result of this prototype development phase is a “master mold”. The “master mold” is a silicon wafer which has the desired device channels and structures that can be used repeatedly to form batches of devices. The first step in developing the prototype is the spin coating of a negative or positive photoresist on a *clean* silicon wafer. The emphasis on clean is of crucial importance in nanotechnology device fabrication in general. In fabricating nanodevices, dust plays the role of the adversary. Dust particles may not be completely captured by the naked eye but wreak havoc in the fabricated chips. Typically, fabrication requires “clean-room” facilities that are dust free environments, specially designed to support nanotechnology research. However, the maintenance and use of these facilities often incur extensive costs. To reduce costs as well as ensure rapid prototyping, researchers conduct their work in normal lab settings. However, they ensure that the labs are very clean. Further, before using silicon wafers for the “master mold” they clean it up by a blast of high pressurized nitrogen, as well as with ethyl alcohol, if required, ensuring that any dust particles are removed. The chemical processes involved in the fabrication are typically conducted in a fumehood.

The silicon wafer is then coated with a calculated amount of photoresist material (positive or negative depending on the procedure). Photoresist materials are polymer based resins, sensitive to ultra violet (UV) light. In order to be usable, they should have a property of being sufficiently viscous to ensure proper coating of the wafer. At the same time, after exposure to the UV light, they can be removed. Photoresist materials can be either positive or negative. A positive photoresist produces an image that corresponds to the image of the mask. Once it has been chemically reactive with the surface of the wafer, the exposed regions are made soluble and removed. In contrast, the negative photoresist works just the opposite. As a result the photoresist treatment (positive of negative), changes the structure of the wafer. Thus this presents new opportunities for working with the wafer. For example, the wafer was transformed from having a plain face to one having grooves or channels etched into it. This transformation was brought about by materials that collude together in a particular manner. The workability of the photoresist should be such that it allows for optimal spreading over the wafer as well as its removal once the process is completed.

At the same time, along with the workability of the photoresist material, there is considerable skill required on the part of the person involved in the fabrication process. Dexterity is most visible in the coating process. Coating the photoresist on the spin-coater is not a straightforward process. The spin-coater is a device with a turntable that spins at a very high speed. When a wafer is placed on the turntable and the required amount of photoresist is poured into it and made to spin, the material spreads all over the wafer in an even manner due to the centrifugal force induced by the spinning. In an ideal scenario, the spin coater produces an even coating. However, as the observation revealed, the even coating was largely the product of the skill of the fabricator. To make the previous statement intelligible, let us consider the example of a glass slide which is to be spin-coated on the turn table. The quantity of photoresist material for a fixed thickness of coating has been calculated initially but actually getting the appropriate thickness was a challenge. This main challenge is faced when the photoresist material has to be poured in a manner so as to ensure an even surface coating in all directions. Finding a solution is not straightforward. The challenges in the process can be broken into two subcomponents. First, the glass slide has to be properly aligned with the turntable. Second, the photoresist material has to be applied in a manner so that the coating is even. For the first problem of alignment different participants approached the problem differently. Some participants placed the slide on the static turntable with careful precision to ensure the fit before starting the turntable rotation. Another participant placed the glass slide carefully in the middle and rotated it for some time so that the centrifugal force aligned the glass slide to the turntable. A third participant focused on the area that would pertain to the extreme end of the rotating slide. The logic employed is simply that the two ends of the glass slides will pass through the area while rotating. This step was repeated for another area corresponding to the antipode of the previous area or the rotating slide or wafer. If two subsequent extreme edges chart the same path in the area of interest then the wafer is centrally aligned.

Once the wafer is aligned the problem arises for the placement of the photoresist material such that the spread is even over the surface. This poses a problem too. Returning back to the example of the glass slide, imagine pouring the material in the centre of rotation. This scenario provides a distribution that is proper in the middle but tapers towards the ends. A different method could involve placing the material in the glass plate in terms of a central long line. This produces a criss-cross pattern of alignment and at times may cause uneven deposition on a few sides.

Needless to say, there is no sure-fire method of spin-coating to ensure proper outcome. However, individuals devise their own optimal methods that suit them best. One method, even though a bit painstaking, provided a more even finish than the others. In this method, the researcher went about pouring the material in the following order, in the areas numbered below, before turning the turntable. Such a method of making two centers and connecting them with a bridge led to a more even spread. Along with this, the participant mastered the amount of the material to be placed at these locations to ensure an even spread. The challenge of coating the glass slide is a demonstration of the hidden dimension of workmanship that exists in lab practice in LOC technology.

Thus, coating a wafer with the photoresist is not a simple act but best conceptualized as a resultant of a severe tussle between the material, the external forces applied by the spin coater and the dexterity of the individual creating it. The photoresist-coated (or PDMS coated) wafer is an emergent whose final outcome is at any time never guaranteed. The spin coating process denotes the “workmanship of risk”. Another important aspect to be gleaned from the process of spin coating is the nature of knowing and acting that is distributed between the individual, spin-coater and the material. The spin-coater should not be considered an instrument that spits out finished products, rather, in the process of spin-coating, the person learnt the manner in which to use the spin-coater in order to produce the result he wanted, given the workability of the materials at hand (Figure 4.4).

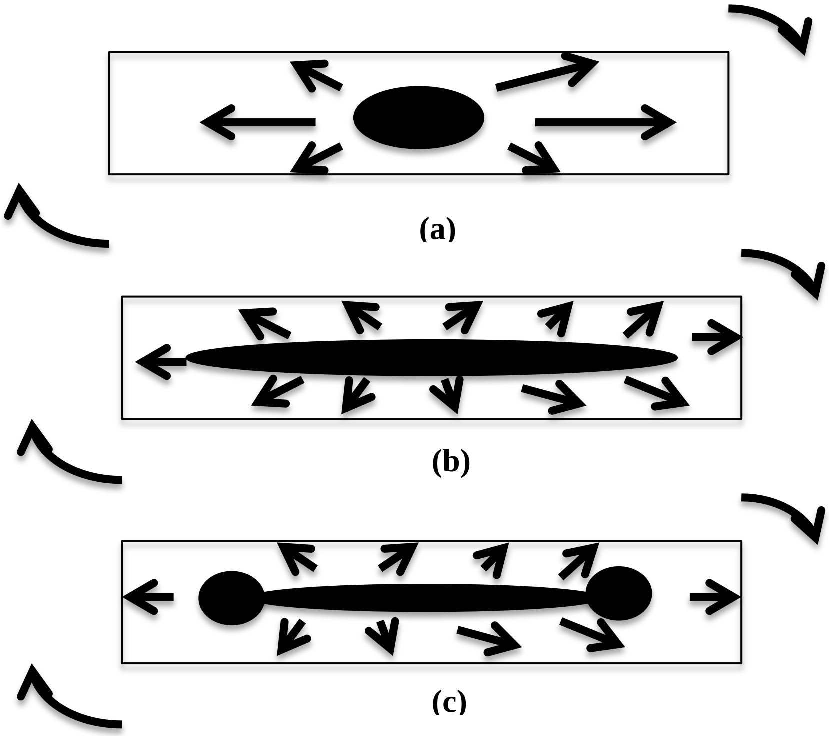


Figure 4.4: Viewing a glass slide from above. The three plates a,b,c show the various ways of pouring the liquid on the glass slide to coat it evenly on a spin coater.

Figure 4.5: Glass slide that did not get coated properly

Figure 4.6: Glass slides that are discarded due to improper coating

After the spin-coater is used to successfully coat the silicon wafer, the photomask is placed on the wafer and the UV light is applied. The UV light exposure system is also complex. In the microfluidics lab where this study was conducted, a sign posted on the wall next to the UV exposure system cautions the users to be careful and asks them to get in touch with senior graduate students in order to learn to operate the machine before using it directly. The UV exposure system also exemplifies “thing knowledge”. Controlling the precise amount of UV exposure is essential for developing the “master mold”. This involves setting up the precise voltage and current for the lamp intensity as well as the exposure time. In a mélange of appropriate combinations of dials and knobs, the researchers set the optimal conditions for exposure enabling the photoresist coated to be UV exposed for a specific time (Figure 4.7). There exists a calculated time for the exposure depending on the materials and the technical specifications of the machine. Overexposure or underexposure may damage the silicon wafer or render it unusable. In one case of underdevelopment, the boundaries of the channels in the master mold did not develop properly. This condition rendered the entire silicon wafer unusable. Thus, along with other factors, cost of the materials also plays a role in the workmanship of risk. Silicon wafers and the materials required to etch it are expensive. Therefore, researchers try to ensure that the wafers are not wasted.

Also, the UV exposure system can be used to develop molds with multiple layers. Multiple-layer development presents additional challenges. After the photoresist has been exposed, the unused portions are dissolved by a photoresist developer. The photoresist developer does not dissolve those areas that have been exposed to UV light as they become insoluble. Once the unused photoresist is dissolved, the silicon wafer is now ready to be used as a master mold. Typically, in each master mold, five or six devices are etched, depending on the size of the LOC. Master molds can be developed in layers, if it is required, based on the technical design. However, this particular lab focused on a single-layered device development. More layers would require a complex process and would add to the “workmanship of risk”. As already described before, the entire process is pervaded by the delicate balance of materials and workmanship and instrument-based knowledge of the researcher with a persistent ambiguity about the outcome. The outcomes are not predetermined but emerge; the researcher qua workman ensures that the outcome is transformed from materials to a master mold and later into a working device. The creation of a master mold serves as the basis for future devices and hence, the researcher carefully inspects the surface of the master molded to ensure that there are no discrepancies and faults in the layout. Once the master mold undergoes this visual inspection and is deemed workable, it is then used for creating the device.

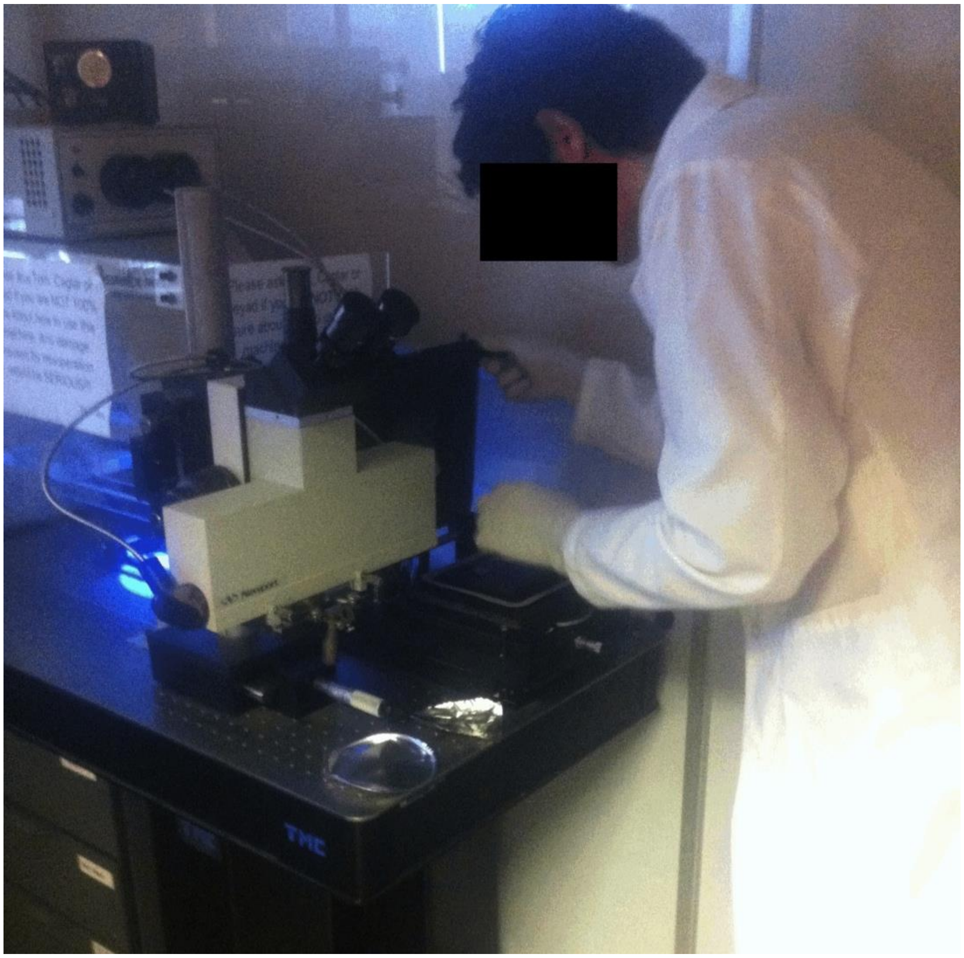

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Figure 4.7: UV treatment of the wafer. Blue light is the UV light. Special precaution is taken not to stare into the light and to use of appropriate eyeglasses while using the UV light equipment.

4.1.7.3 Molding the material PDMS

The process of device creation from the master mold consists of three subprocesses. First, creating a PDMS mold from the master mold. Second, creating the entry points for fluids for the final device. Third, bonding the PDMS to the glass slide and thus producing the device. The first step in a creating PDMS mold is to recognize that the master mold will serve for the production of different PDMS materials; i.e., the PDMS should not remain stuck to the surface in the process of demolding. Therefore, the surface of the master mold is coated with a silanization agent. A silanization agent makes the surface of the silicon wafer passive and later allows for the easy removal of the PDMs substrate. Thus, it makes the workability of PDMS better. However, the silanizing agent, Trimethylchlorosilane (TMCS), is highly corrosive and thus is handled with extreme caution. In order to conduct silanization, a few drops of TMCS are placed in a glass petri dish along with the master mold into a vacuum chamber for the designated amount of time. The vacuum allows the TMCs to evaporate and coat the silicon wafer.

The process of creation of the PDMS substrate is best understood as the transformation of materials from a raw form to a finished form. The PDMS used in the process begins in the form of a PDMS base that is mixed with a catalyst in the ratio 10:1. Then this mixture is made homogeneous using a mechanical mixer. The mixing process may introduce air bubbles. Air bubbles can be removed by degassing (Figure 4.8).

Figure 4.8: The white froth is air bubbles. For removing the air bubbles, it is placed in the degassing chamber

Once the PDMS becomes bubble free, it is poured on the master mold. In order to achieve this, the master mold is placed in an aluminum casing and then the PDMS liquid is poured over it (Figure 4.9). Both the aluminum foil and silicon wafer are cleared by a blast of high-pressurized air to ensure that no dust particles are present on the surface. Once cleared, the PDMS is poured into the mold. Further, it is ensured that no air bubbles remain in the PDMS. Air bubbles cause devices to be formed incorrectly. Once done, the wafer and aluminum sheet are placed on a flat oven for about one hour. The temperature of the oven is around 80-90 deg.C. Once this curing process takes place the PDMS becomes stable. The transformation of PDMS started from the form of a fluid base and ended as an elastic solid after being baked for an hour on the hot plate (Figure 4.10). At this point the baked PDMS feels like a hardened piece of jello. The next step is to demold the jello-like PDMS and punch holes into it.

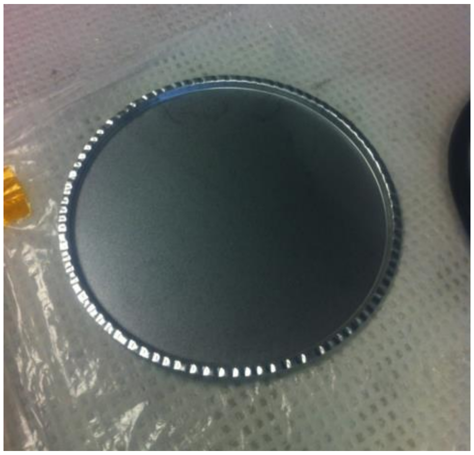

Figure 4.9: Aluminum foil for serving as the base of the wafer during molding

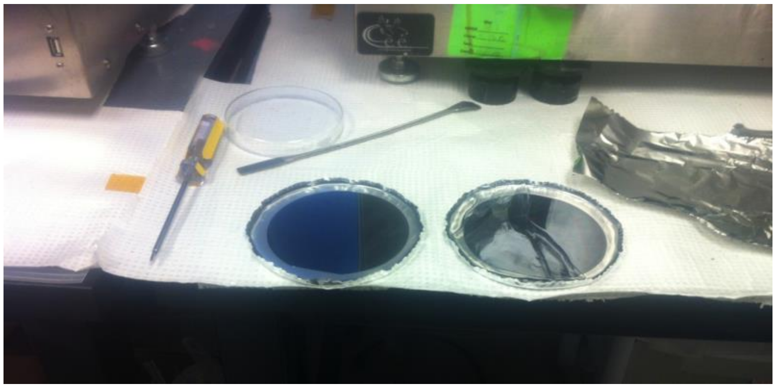

Figure 4.10: Even molding of PDMS on the left and uneven molding on the right

This next step brings the process of fabricating the chips, back into the realm of haptic awareness of the body. Earlier, beginning with the chemical processes of making the PDMS mixture from the base and catalyst, silanizing the wafer and baking the PDMS requires conducting these activities in a manner that keeps the processes typically away from the body. This is due to the harmful chemicals involved in the process. The transformation of the workability of the materials is shifted from the realm of vision to that of touch. Viewing harmful chemicals to understand their workability is replaced by touching the hardened inert PDMS to work on it. In other words, after baking the PDMS, it becomes relatively solid and the demolding process is more personal, involving a bodily knowing that could not be possible in the previous step. Once the PDMS hardens, it acts like a hardened piece of jello, retaining elasticity but at the same time providing resistance. The first step in removing the PDMS involves removing the aluminum foil from the back of the wafer (Figure 4.11). Next, the PDMS is slowly peeled from the wafer and covered with a sheet of extremely thin transparent plastic wrap. The plastic ensures that the exposed surface that will be later molded is not in contact with the dust. As mentioned before, dust is anathema to LOC researchers. Once the plastic wrap is in place, the researcher proceeds to cut out the extra pieces and the devices that were obtained from one mold. Placing the plastic wrap on the PDMS has another effect. It makes the entire surface translucent thus to make appropriate cuts, the researcher often brings the PDMS close to a light to see the details clearly before proceeding with the cuts.

Figure 4.11: Cutting the PDMS from the mold. The knife is used at the edges to ensure that the mold is not destroyed. The freed PDMS will subsequently be sliced into smaller pieces.

Cutting the molded PDMS into separate devices is a precarious process. First, PDMS acting like a hardened piece of jello, poses a resistance. In the figure below, shows a horizontal profile of PDMS. The first figure shows the cut which is ideal for the PDMS. However, due to the resistance that the PDMS offers, the cuts often end up deviating from the ideal case. In actuality, the deviated cuts are the norm rather than the exception.

To counter this, the researchers use different approaches. Some use a sawing motion to slowly cut through the PDMS very slowly, whereas others mimic a chopping board. They place the edge of the knife on the extreme end, extending their finger to make the end a fulcrum point, and then use the other hand to hold the PDMS in place. Then they proceed to "chop" the PDMS.

In both the cases, the researchers adopt the particular techniques because they "feel right". However, a mere adoption of technique does not guarantee any success. Both the techniques require complete mastery in making precision cuts. The advanced researchers who have spent considerable time in labwork are often experts in this task. Novices find it difficult to master cutting techniques to produce straight cuts. However, as long as the basic circuitry of the tubes is not damaged, the device still remains functional despite the improper cutting. The next step involves making holes in the PDMS molds in order to allow for the entry of fluids. Making holes is another process which requires skill. Typically, researchers find it amenable to make the holes by hand using a syringe head of a particular gauge. The gauge size of the particular syringe head is comparable to the size of the microcapillary tubes that will be later used in device testing. The needle head used to punch holes is of the following shape.

The punching requires extreme care. If done quickly and with unequal force the surface of entry will crack. A second problem due to the application of unequal force, results in abrasion of the sidewalls of the hole. The material dislodged by the abrasion of this sidewall ends up being forced into the channels by the inflow of fluid; thus, resulting in clogging. Typically, a mechanical hole-punching machine is often used for this step of punching. However, the researchers showed a penchant for manual punching using the above described metal needle; thus, adding to the workmanship dimension.

Once holes are made the PDMS is ready to be connected to the glass slide for completing the device. In order to complete the final step, a glass slide is taken and spin coated with PDMS to form an extremely thin layer. The coated glass slide is then bonded with the PDMS chip. The process of boding is quite delicate. Hardened PDMS has a non-reactive surface. In order to bond it very carefully with the glass slide, its surface has to be made reactive. This is done by exposing the PDMS to oxygen plasma in a vacuum. Along with the oxygen plasma, a standard procedure consists of adding two or three drops of a silanizing agent in a petri dish along with the glass slide and PDMS for roughly around seven to eight seconds. In this lab the silanizing agent was not used in this step. The oxygen plasma exposure makes the PDMS surface reactive. Once the PDMS has been exposed to oxygen plasma, it needs to be stuck to the glass slide immediately. This process requires dexterity and is extremely time-critical. Further, PDMS and the glass slide need to be properly aligned so that the device is functioning properly. However, the result of alignment and bonding cannot be immediately gauged. It is revealed in the process of testing the chip. During misalignment and bonding sometimes chips show aberrations that are difficult to correct; hence, they have to be discarded. Considering the inherent ambiguity of the process adds to the measure of risk in device fabrication.

Another challenge that the researcher *qua* workman faces in the process of bonding is the change in the properties of materials at hand. In its inert state the PDMS is not workable. However, once exposed to oxygen plasma, the bonding can take place. The exposure of the PDMS to oxygen plasma is an extremely sensitive process. On the one hand a too short exposure period will not create the proper surface; i.e., the silanol (SiOH) sites created on the PDMS surface will not be enough to create a strong bond. On the other hand, in case of over exposure, the SiOH sites will be in abundance resulting in a non-bonding silica layer. This fine tuning of the bonding process is rife with uncertainty. To manage the binding process, some researchers have improvised techniques. One of them counts from one to eight in a paced manner for the time that PDMS is exposed to the silanol in the plasma chamber. Whereas, another counts from one to ten quickly. In terms of a consistent time measurement, roughly seven to eight seconds was noted. Both the above mentioned researchers roughly used the same time for their idiosyncratic counting. After the exposure to plasma oxygen, the materials are taken out and, using a perceptual-haptic judgement, quickly stuck together. This is an extremely time critical task and is often rife with uncertainty. The device can easily get damaged and the efforts behind the activity outlined above can easily be wasted due to the PDMS not being properly bonded. In one case, one researcher made ten devices in a day. Finally after the PDMS bonding process, he found that two devices were not bonded properly, one device had a glass with a crack which got exacerbated after the baking process and two other devices were not bonded properly in the middle thus presenting a fluid accumulation in the device. The failure of the last two devices came only to be known once the device was tested the next day. In short, out of the ten devices, only five worked and even then posed problems with debris stuck in the parts of the tubing of the device. It is not surprising that the researcher *qua* workman is in constant state of preparedness to create the device which reflects the “workmanship of risk”.

Once the PDMS and glass slide are bonded, they are placed on the hot plate for further baking. The baking process takes place in two stages. First, the device is placed on a lower temperature of 65 deg.C. Later it is placed on a higher temperature of 95 deg.C. This is done in order to avoid heat stresses in the material. The device when exposed to high temperature may be heated unevenly on the two layers. The layer in contact with the heating plate will have a higher temperature whereas the layer exposed to air will have a lower temperature. Hence, this will cause a heat gradient and uneven expansion of the device introducing unwanted thermal stress. Therefore, the device is heated at a lower temperature and then at a higher one. In order to cut the turnaround time of research, some researchers conduct the entire device fabrication in the late afternoons and early evenings. Thus, having left the device at a lower temperature for a few hours, they transfer it to the hot plate with higher temperature and leave it for baking overnight. These devices are ready for testing the next morning (Figure 4.12).

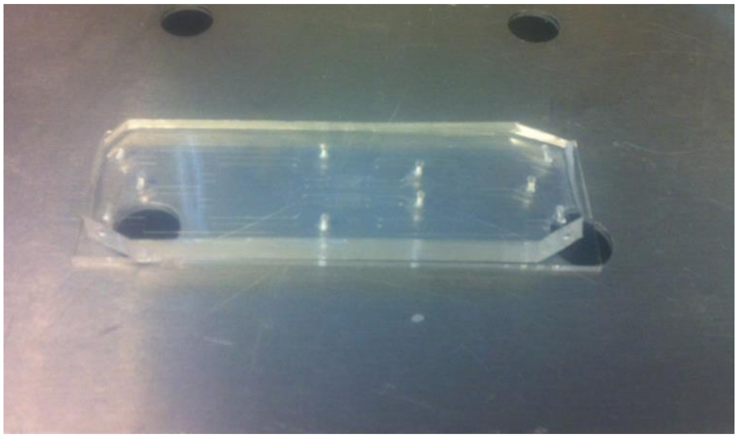

Figure 4.12: Completed LOC device. The punched holes are evident in the figure. The circuitry of tubules is difficult to view unless placed at an appropriate angle towards the light

4.1.8 Phase 2—Activities involved in testing the chip

After the device has been created, the researcher's role changes from the workman (synthesizer) to that of an analyst. Further, other changes also occur concomitantly. For example, dust, which presented a major problem during the fabrication stage, recedes into the background during testing. In the testing phase, the debris emerges as the new challenge for the analyst. Further, the testing phase of LOC devices requires considerable understanding of the instruments associated with testing it. Three main instruments are involved in the testing process — pressure controller, microscope and computer (software). All the three are connected to each other and the LOC device to form a closed flow of fluid (Figure 4.13). The flow from the pressure controller to the device depends on the length and diameter of the tube connecting the LOC and the relative height of the components. For this reason, the researchers use precise lengths of tubes and have the LOC device placed at fixed level under the microscope (Figure 4.14). The tubes must be placed such that a constant flow is maintained throughout the device. In short, the device should act like a component in a flow circuit in order to gain proper measurements.

Figure 4.13: Setup for testing. Pressure pump is connected to the inlet and outlet of the microtubules. The tubes are provided connecting the pressure pump and LOC device in a closed flow circuit. The computer is connected to the microscope for a closed loop for information and data collection.

Figure 4.14: Researcher setting up equipment for testing. The device is placed under the microscope. The present microscope has a movable head position that is placed back in the figure, to allow for setting up the device under it. After setting, the microscope head will be positioned back to normal for recording the head.

Typically, the lengths of the tubes are minimized to ensure stability of the flow; also, an outlet tube is also provided to collect any flow that spills out of the device. In general this waste outlet has to be placed at a lower pressure relative to the inlet. Since there is no suction placed at the outlet, the inlet pressure should be maintained higher than the outlet. The choice of fluids in the channel depends on the purpose for which the device is designed. For example, two immiscible liquids could be used such that it allows for one liquid to be regulated as drops while the other liquid fills up the flow chamber between the drops. Many combinations of fluids can be used. Further, the fluid flow can also be regulated by applying electromagnetic fields depending on the application. The fluids are generally placed in bottles connected to the pressure pump. The pressure controller regulates the pressure in the device. It allows for fine-grained control that allows for data acquisition. The pressure controller requires a period of stabilization; therefore, it is generally turned on for ten to fifteen minutes before recording any measurements. In the first step of testing the chip, the chip is connected to the pressure controller and started with low values of flow rates. Later these flow rates are gradually increased to reach the experimental parameters. Researchers observe caution while increasing the pressure. Excessive pressure in the tube leads to the rupture of the device. Further, excessive flow in the beginning of the testing pushes the debris into difficult corners of the tubing, making it extremely difficult to dislodge (Figure 4.15). Dislodging can be tried by increasing the flow. However, there is a potential for damage in terms of rupturing the device.

Testing is the stage when the results of workmanship are finally revealed. During inspections many devices show that the bonding was not properly done or debris remains in the channels. Sometimes in order to remove the debris researchers increase the flow pressure. However, this may also cause damage to the device. Devices sometimes rupture due to increased pressure (Figure 4.16). Sometimes, reversing the flow allows for dislodging debris stuck at extreme corners; this strategy, however, may not be successful all the time. Another problem related to debris that often occurs in the device is due to materials loosening from the wall where the holes were punched in the PDMS (Figure 4.17). When the fluid flow begins, this debris gets loosened and clogs the inlet of the device. Thus, the results of punching holes are only revealed at the end of the process of device fabrication.

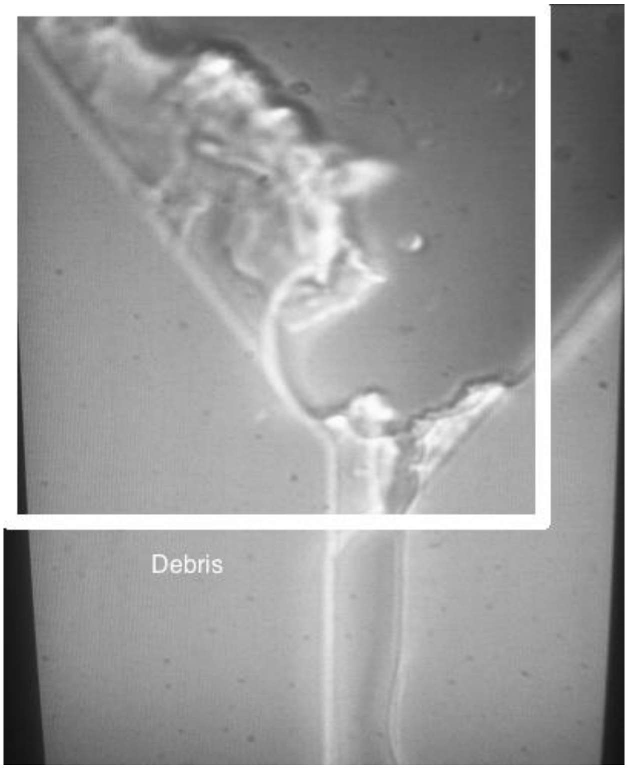

Figure 4.15: Debris stuck at the inlet of the device due to improper fabrication

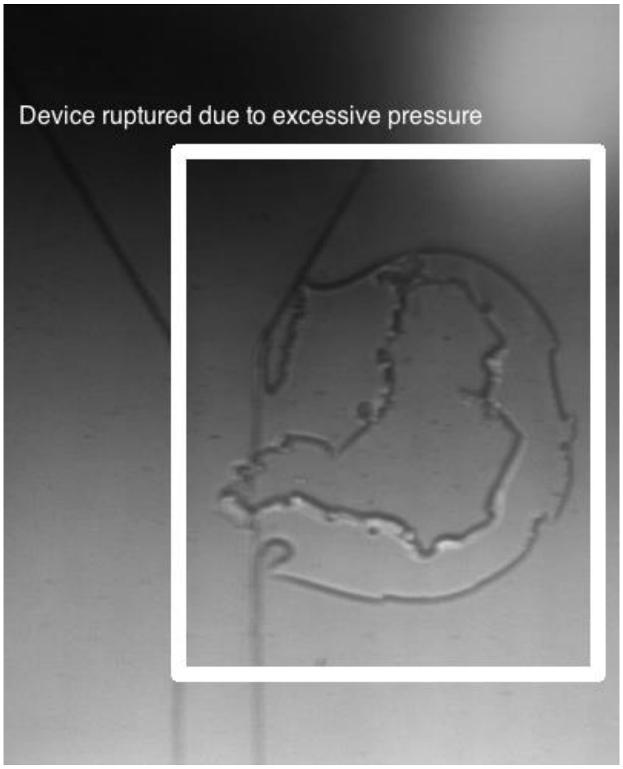

Figure 4.16: Excessive pressure for clearing the debris caused a rupture in the wall of the tubes. This device had to be discarded

Debris, from the viewpoint of the researcher, is something to be removed from the microfluidic channels. However, this minor speck, invisible to the naked eye, often shapes the researcher’s workday considerably. Typically, once the debris is removed, the system needs to be stabilized before readings can be taken. Not surprisingly, the researcher tries to maximize the number of readings. Thus, an experiment started early in the morning would sometimes take about an hour or more for the experiment to be simply set up and running. Once the system is set up, one specific researcher had a habit of taking continuous recordings with a half an hour lunch break in the afternoon. The second half an hour break was taken at five in the evening. Finally, the experiment was wrapped up at ten at night. This particular researcher took intensive recordings for three days and then analyzed data for the next three. Even though experimental regimes of other researchers were not always this extreme, nonetheless, the debris of the microfluidic channel was a key aspect that shaped the researchers' work routines.

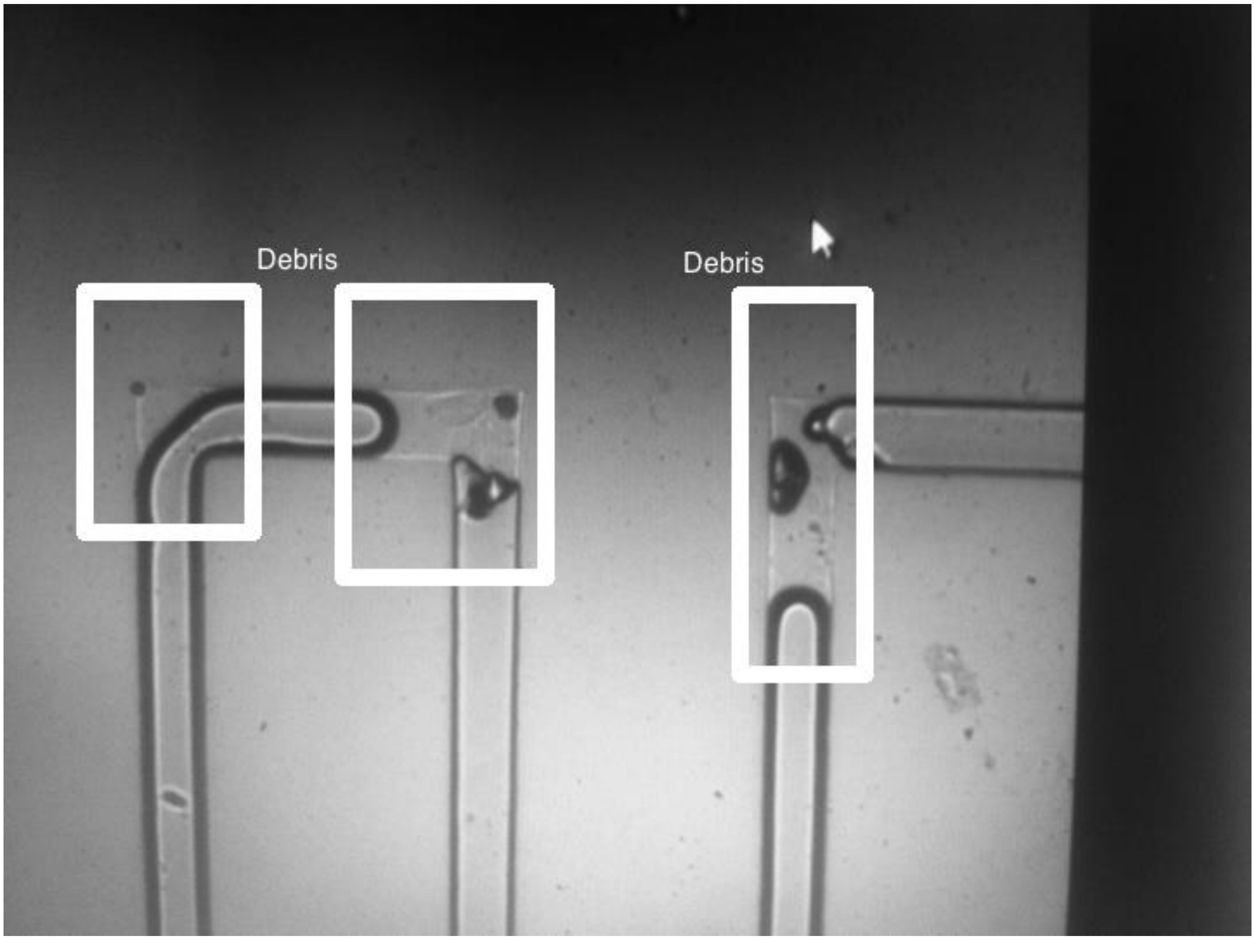

Figure 4.17: Debris stuck to the walls of the tube

Debris is just one of the many problems faced during testing. Another challenge that researchers constantly face is that of slow rate of fluid flow through the channels. The rate of fluid flow is suited for the research purposes, however, due to the initial setup and slow pressures, the time required for the fluid to reach the device initially is quite high. In other words, due to less pressure initially, tubes connecting the device fill up slowly. In order to cut the turnaround time short, researchers improvise in the following manner. They first dislodge the tube from the device and apply high pressure. Once the fluid reaches three fourths of the length of the tube, the pressure is decreased and the tube is inserted back into the device.

Another problem faced in the circulation of the fluid is that of backflow. In backflow, a drop of fluid 1 enters the flow channel of fluid 2 and ends up moving towards the pressure pump (Figure 4.18). In order to stop this situation, the tube of fluid 2 is disconnected and the drop of fluid 1 is ejected. Discarding the drop of fluid 1 is a disturbance in the course of the experiment, as the drop has to be removed. It takes time to take the drop out, refit the tube, bringing the device to a steady state and at the original state of flow. To counter this situation, researchers improvise. One researcher used a long tube to connect the outlet of flow 2 and the pressure controller. For low pressures, the fluid 1 drop movement is slow; hence, this allowed for a stable recording for a considerable amount of time. As soon as the fluid drop comes close to the pressure controller, the tube is disconnected and the drop is allowed to escape before the tube is connected back again. Once the device is ready for measurement, the microscope and the camera attached to it are turned on in order to gather recordings. Based on the requirements of researchers, the camera-recording rate and other parameters are set.

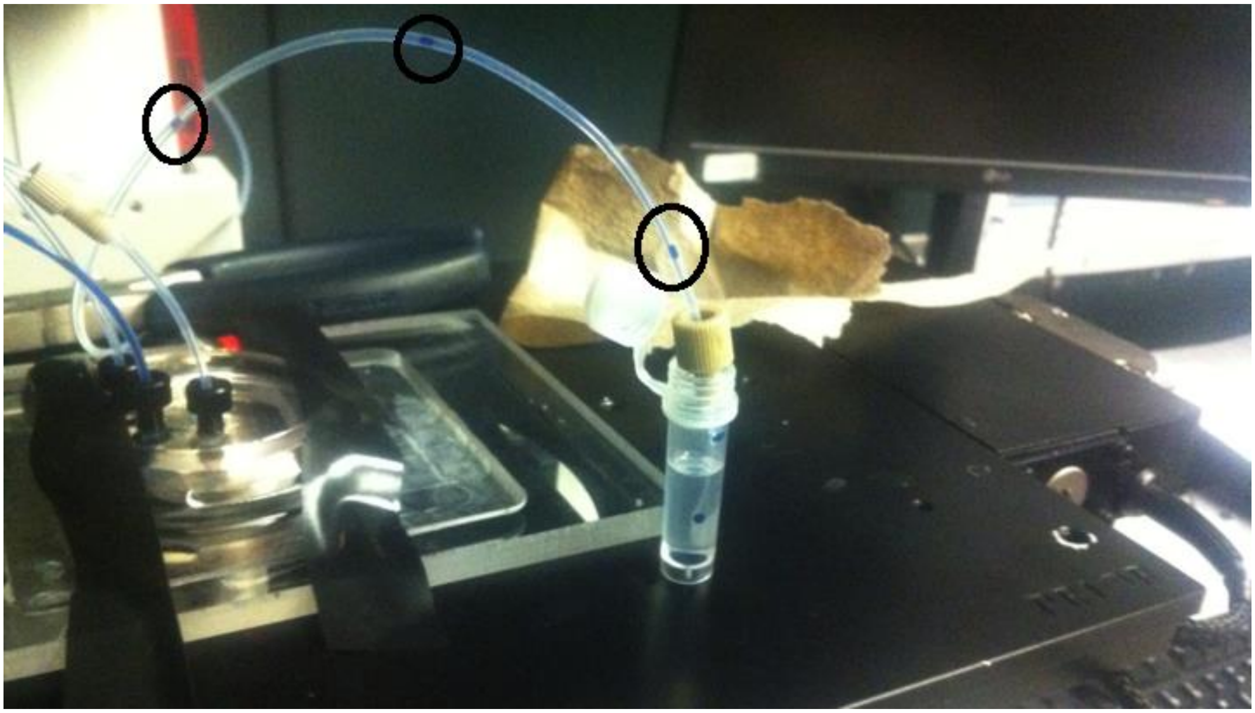

Figure 4.18: Condition of backflow. Notice the colored drops of fluid 1 in the clear fluid 2

Both the camera and the pressure pump are controlled by computer software. The software controlling the pressure pump is generally provided by the company that had manufactured the device. At the same time, the research lab of which I was part of used the software Laboratory Virtual Instrument Engineering Workbench (LabVIEW). LabVIEW is a systems design and development software environment that is used in areas of data acquisition, instrument control and embedded systems design, among others. The interface that the researchers used in this lab setting was in terms of individual indicators, similar to single-sensor-single-indicator displays from erstwhile interface technologies. Thus, the task of knowledge discovery is entirely placed on the researcher. Interface design principles can aid the process of creative research by helping the researcher to make appropriate connections between variables to understand the nature of activity occurring in the LOC devices. HFE, thus, can play a major, but invisible role, in nanotechnology research.

Along with the interfaces for data acquisition, microscopes also play a major role in microfluidics and nanotechnology in general. Microscope software also provides image and video acquisition characteristics that are important for conducting research. HFE can again play an invisible but highly crucial support for the design of interfaces for microscopes specifically geared towards microfluidics research. The use of instruments and flow pumps also require an understanding of the ways of knowing and acting required to operate the equipment successfully, gather appropriate data robustly, and analyze data creatively to make analytical discoveries.

4.1.9 Generic Processes, Challenges and Ambiguities

This study was conducted in university laboratory settings in order to study the fabrication and testing of LOC devices. The LOC devices in the current study were fabricated by soft lithography techniques. The ethnographic study was divided into two major phases — fabrication and testing. In the fabrication phase, the chemicals were used to form a master mold on a silicon wafer. This master mold was used to form inert PDMS blocks that were later bonded with glass slides to make the LOC device. After fabrication, these LOC devices were tested to ensure that they were functioning correctly.

Over the course of the study, three important aspects were highlighted. First, LOC device research considerably involved aspects of activity that can be labeled as *situated,* both during fabrication and testing. In fabrication as well as testing the device emerges as a result of the itinerary of chemical reactions and orchestrated improvisations on part of the researcher. Second, the device fabrication (understood as making as activity) entailed a considerable degree of workmanship and ambiguity on the part of the researcher while fabricating the chips. Workmanship refers to the degree of skill by which the device is made. Workmanship involves judgment, dexterity and care required to create the end product. As shown in the ethnography, even though the design of the device was conceptually correct, the fabrication posed several risks. Beginning with the creation of the master mold to the bonding of the PDMS to the glass slide, at each step there is a possibility for the fabrication process to go wrong. As a result, the task of the researcher involves exercising dexterity, judgment and care during the fabrication process. Related to this notion of workmanship, a second important aspect to be highlighted was the notion of "workability of materials". Workability refers to the ways in which the various materials could be manipulated. These three points are discussed below in greater detail.

4.1.9.1 LOC research as situated activity

In HFE, researchers from various schools of thought have emphasized that cognition and activity in situations is contextual and emerges as the situation unfolds (e.g. see, Hutchins, 1995; Lave, 1988; Lave & Wenger, 1991; Suchman, 2007; among others;). Suchman (2007) addresses the notion of activity by highlighting that actions are primarily situated in nature; i.e., they have to be understood in "the context of particular, concrete circumstances" (p.26). Suchman's emphasis on actions as situated, lies in contrast to actions as characterized by plans. Typically, when activity is characterized in terms of plans, it is depicted in terms of the actors, their intentions and the possible steps to achieve the outcome. In contrast, from a situated activity perspective, plans as a *complete* characterization of activity is a myth. In any given case, there are multitudes of ambiguities and perplexities that individuals face during the course of action. The resultant improvised activity is shaped by innumerable aspects, ranging from the material to the social. Thus, activity from the situated perspective is best characterized as emergent. In this emergent view of activity, plans can be best described as representations of action. These plans are abstractions in form of possible imagined accounts of activity or retrospective constructions.

The distinction between plans and situated activity is also visible in the LOC device domain. The device creation is often described in terms of a sequence of actions (a plan, see Fig. 3) prescribed by a scientific recipe. However, the ethnographic study revealed that the actual activity was composed a myriad of constraints and contingencies that had to be negotiated by the researcher in order to create the device. The notion of situatedness of activity, as compared to the initial plan, is strongly reflected in both the fabrication and the testing of the LOC device. At each instance in the development of the chip, researchers are faced with physical and cognitive[19] challenges that they solve *in situ*. The physical challenges related to the fabrication involve instances such as the processes of pouring PDMS, cutting the PDMS pieces, bonding the PDMS with the glass slide, among others. . The creation of LOC devices observed here shows the critical importance of understanding physical and cognitive requirements together in context with the capabilities of the researcher. At each instance in the process, the outcome of the activity is not predetermined; the results are contingent on the process, the outcome is emergent. In many cases, this emergent result is undesirable; i.e., the bonding of the glass slide and PDMS may not occur properly resulting in the device to be discarded. These decisions as well as many others made over the course of the process, constantly reshape the researchers itinerary as they progress in their research agenda.

A cognitive view of this environment would have revealed the necessary constraints for the device to work properly, the skills and knowledge of the researchers involved, and the information processes and strategies that took place. However, in understanding where failures occur in this context, the role of workmanship was important in the construal of situated knowing. Not only did researchers understand cognitively the processes they were managing, the best researchers had a deep physical appreciation of where materials would fail and the physical consequences of their actions.

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[19] The terms physical and cognitive have been separated here for the sake of saliency of depiction. In a few cases of chip fabrication the “physical” aspects of activity are prominent, while in other cases of chip testing the “cognitive” aspects are salient. However, even though these distinctions are made, no ontological split is intended between these terms.

A good example of this was seen in coating the slide. The researcher needed to have more than a cognitive understanding of the viscosity of the photo resist material but also, and possibly more importantly, a very physical understanding the viscosity. This understanding the viscosity was in relation to their own understanding or experience of their dexterity. Coupling these together, the researchers sought and found the most effective strategies for coating the chips. A similar challenge was seen in cutting the molded PDMS. From sawing to chopping, the strategy chosen was natural combination of the researcher's physical abilities and the workability of the material they were encountering. Making holes and bonding showed similar challenges.

Along with the physical challenges in the fabrication stage, the cognitive challenges become paramount in the testing stage. During testing, the researcher has to take into account the various sites of debris and their effect on the overall chip. As mentioned before, removal of the debris depends on the site in which it occurs. In many cases, the debris cannot be completely removed. Therefore, the challenge of the researcher is to make decisions whether to retain the device based on project criteria or discard it. These questions related to debris as well as other challenges for the flow in the device constantly arise in the testing phase. Each of the answers requires not only a generalized understanding of the project but also a detailed understanding of the situation as it unfolds.

Situatedness of activity involves an improvisational view of the work domain under consideration. Even though the soft lithography process is substantially generic and standardized, its orchestration and use in every research scenarios requires local construction of action and range of localized choices that the researcher is constantly involved in throughout the process. Along with these localized considerations that emerges *in situ*, attentional demands on part of the researcher are also present. The researchers' involvement requires concentrated attention during fabrication as well as the testing of devices. At every instance, the attentional demands modulate the cognitive as well as physical activity. In case of fabrication, the attention and physical activity go hand in hand to produce the device. Whereas, in case of testing the device, cognitive activity involves concentrated attention for identifying debris and the associated feasibility of the device for data collection. The dimensions related to the physical and cognitive activity along with the attentional demands required for the LOC device highlights the situated nature of nanotechnology research settings.

4.1.9.2 Making as activity; Ambiguity and the Workmanship of risk

In this particular domain, along with the salient aspect of *in situ* construction of activity, a related aspect is the degree of workmanship and concomitant ambiguity involved in the fabrication. Even though researchers design their devices conceptually, based on the scientific concepts and equations, the device fabrication in the lab entails a considerable degree of workmanship. The difference between design and workmanship can be addressed in the following manner: “Design is what, for practical purposes, can be converged in words and by drawing: workmanship is what, for practical purposes, can not” (Pye, 1968, p.1). The difference between design and workmanship is similar to plans and situated actions (Section 3.1); workmanship is inherently performative. However, performative workmanship corresponds to a specific activity of making. Making as an activity involves fashioning of entities from materials, bringing them together in ways such that the resultant is a creative endeavor. Making is inherently improvisational and processional (Ingold, 2013, 2011, Ch. 4). In the case of the LOC device at the end of the process of fabrication, the materials were fashioned into a working device. This transformation was brought about by the workmanship of the researcher. Workmanship involves a considerable role of dexterity on part of the researcher. Further, the risk of damage at any time in the process is a key aspect of making LOC using soft lithography techniques. Specifically, in the case of fabrication of LOC devices, the workmanship is labeled as the “workmanship of risk” (Pye, 1968, p.4). Therefore, the “workmanship of risk” involved in this case can be characterized as,

> “[…] any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making; and so I shall call this kind of workmanship ‘The workmanship of risk’: an uncouth phrase, but at least descriptive”. (Pye, 1968, p.4)

While workmanship is definitely a performative and situated activity, it forms a unique subclass of performance in which the actor produces an entity. Here the actor’s judgment, dexterity and skill are to be emphasized. Making as an activity in LOC devices involves considerable ambiguity. To counter ambiguity, the researchers (qua workmen) had evolved their own strategies of addressing the materials. This involved application of certain amount of force while cutting, ways of punching holes in the PDMS, among others. These activities, definitely labeled as situated, also involved a certain amount of judgment, care and awareness of the self and the material with a view towards making and creating. Thus, while all chips were made by the situated activity involving the researchers, the researchers who had improved the quality of their workmanship were able to produce more number of working chips.

Typically, dexterity and workmanship are explored in the literature related to physical ergonomics. At times, workmanship is also synonymously used with craftsmanship and is relation to quality in products (e.g. Bhise, 2011, Ch. 10 and Yun, You, Geum & Kong, 2004, for craftsmanship in vehicles; Iwaro & Mwasha, 2012, for relation between workmanship and quality; Colombini et al., 2012 for relation between ergonomics and craftsmanship). Dexterity, a core component of workmanship, also appears in context of skilled manual activity related to HFE (e.g., Dianat, Haslegrave & Stedmon, 2014). However, as the LOC research reveals, the physical and the cognitive together should be understood to provide a holistic picture of the work domain under consideration.

Workmanship, specifically involving risk and ambiguity, is observable throughout the fabrication process. The first step in the process of fabrication involved the etching of the silicon wafer to form the master mold. This process involves a high amount of risk and ambiguity. If the etching of the silicon wafer is not correctly done, then the master mold is faulty, resulting in improper devices. The etching process required considerable care on behalf of the researcher. The use of chemicals as well as exposure to UV light posed a considerable challenge. If the wafer was not treated with chemical properly or the exposure time was not correct, the master mold would not be formed correctly; subsequently leading to improperly formed devices.

Along with the challenges posed by the master mold, the liquid PDMS needed to be degassed in order to remove trapped air bubbles. During the pouring of the liquid PDMS in the mold, the researcher takes extreme care to pour the liquid slowly to avoid introducing new air bubbles in the liquid PDMS. The liquid PDMS has to be poured in manner such that it results in an even molding. Uneven molding makes the cutting of solid PDMS difficult; thus, it may later result in improper device functioning, due to uneven cutting or damaging of flow circuitry. All these various aspects related to the device adds to the amount of risk involved in the fabrication process.

Another source of risk is the removal of the solid PDMS from the master mold. During this process, the PDMS is carefully removed and wrapped in plastic sheet to avoid dust. This PDMS is later sliced into individual pieces. The slicing of PDMS requires considerable skill. The PDMS acts like a hardened piece of jello and resists cutting. Thus, the researchers, based on their experience and awareness of their own dexterity levels, devised optimal ways in which to approach the task. Typically, LOC chips are not understood in terms of human dexterity and workmanship. However, this ethnographic research reveals that the bodily based tacit dimension of dexterity, played a crucial role throughout the fabrication process. This bodily-based knowing was difficult for the researchers to articulate. However, after observing the researchers for some time, one of them invited the first author to get a first-hand feel of devising the chip. Cutting the PDMS to appropriate dimensions provided the first author with a key insight into the bodily-based non-verbal processes in fabrication that were previously missing from the observations and discussions of the LOC design process.

Along with the slicing process, punching holes also required considerable skill as well as simultaneously posed a risk. As described earlier in the ethnography, if the holes are punched incorrectly, then the fluid flow in the device will be improper, adding to the risk of device failure. Another source of risk in the fabrication process is the bonding of PDMS and glass slide. In many instances the bonding may not be proper, leading to the seepage of fluid out of the network of capillaries in the LOC device.

To summarize, the risk of damage at any time in the process is a key aspect of fabricating LOC using soft lithography techniques. Even though the design was conceptualized earlier, the process of device fabrication was not. The LOC device emerged as an end product of a long process in which the researcher was averting risk while exercising judgment, dexterity and care in various stages of device fabrication. Thus, the entire process of fabricating LOC devices using soft lithography process in the lab can be characterized as the “workmanship of risk” (Pye, 1968, p.4).

4.1.9.3 Using Materials; Workability of materials

Along with the dimension of the workmanship of risk, an interrelated idea is that of the process of using materials or attending to the “workability of materials”. The workability of the materials refers to the properties of materials that allow researchers to manipulate them and bring them to desired form. Typically, this involves perceptual and haptic interactions with the materials. For example, in the fabrication process, PDMS is a made into a viscous liquid to be poured into the molds. The viscous PDMS affords certain properties that can be understood haptically by the researchers; i.e., the viscous PDMS has to be poured in a manner so as to avoid air bubbles. Further, the viscous PDMS has to be poured so as to provide an even coating on the wafer. For this reason, based on the viscosity, over a period of time, the researchers acquire a steady manner in which to pour the liquid PDMS into the mold. This pouring of the liquid PDMS in a proper manner is based on perceptual and haptic knowledge acquired through experience of working with PDMS.

Another example of the change in the workability of materials is observable when the PDMS becomes solid. In this form, the researcher uses a knife to cut the PDMS into strips. In comparison to the older liquid form, the new solid form required a different manner in which the researcher interacts with the materials, both haptically and perceptually. As it was previously discussed, PDMS has certain properties, physical, chemical, among others, making it amenable for fluidics research at the small scale. However, PDMS also presents properties that aid or hamper workability at a perceptual and haptic level. Thus, aspects of workability and workmanship in LOC fabrication mutually support each other. Further, these interrelated aspects should be viewed in terms of situated activity involved in the research settings. For HFE research, in order to study situated activity in research settings, along with the cognitive demands involved in conceptualizing LOC devices, HFE professionals should also note the workmanship involved in devising LOC technology in university laboratory settings. Attending to the situated activity; the workmanship of risk; and the workability of materials will allow for a complete understanding of the LOC settings for small-scale fluidics research.

4.1.10 Conclusion

In the above description of LOC devices, the focus research area was fluidics at the small scale. An ethnographic study was conducted in a university laboratory in a small-scale fluidics laboratory at the University of Waterloo, Canada. In this study the steps of fabricating a LOC device from raw materials and testing it was presented. In particular, the steps involved a discussion of the situated nature of activity, risk involved in workmanship, and the workability of the materials. It was highlighted that along with the scientific character underlying the LOC device, it can be best characterized as an emergent aspect of situated activity, workmanship of risk, and workability of the materials.

This study was conducted in university lab settings in order to study the design of fluidics based LOC device. Over the course of study, a few important aspects were highlighted. First, the device fabrication entails a considerable "workmanship of risk". This workmanship remains invisible in the final aspects of research products. However, workmanship has crucial implications for everyday research activity. Good workmanship allows for less device failure and thus decreases the turnaround time for the research process. Workmanship is also connected to the "workability of materials" and the transformations the materials undergo in the fabrication process. The PDMS begin in a liquid form and is converted into a functioning device. Finally, instruments play an important role in the fabrication and testing process. A large part of knowing and acting in nanotechnology settings involves an understanding of instruments and their use in the process of research. During the fabrication and testing of the chip, the researchers had to face considerable challenges that they solved *in situ*. These challenges ranged from the cognitive to the physical aspects of LOC device fabrication and testing. These situated aspects of the device creation involved a considerable measure of skill, dexterity and risk of workmanship that was supported by the workability of the materials as they changed throughout the course of the fabrication process. The ethnography also unveiled a manner of device creation that complements the traditional science-based view of LOC devices. This nature of the device creation involving human activity is amenable to the research traditions already underway in HFE. This ethnographic study was conducted based on the theoretical perspective of symbolic interactionism and forms the first stage of WIDF. The second stage of WIDF for Devices is presented in the next chapter (Chapter 5). Along with presenting design requirements based on WIDF, the next chapter also compares the requirements with that presented by CWA.

Chapter 5: Site 1—Engineering analysis for Devices

5.1 Introduction

In the last chapter 4, the first step of WIDF for LOC device was presented. This step consisted of ethnography in a small-scale fluidics research laboratory. In this present chapter the second step of WIDF will be detailed. This second step consists of engineering analysis, which will provide design requirements. Along with presenting the second step of WIDF, this chapter also presents requirements derived from CWA. In developing the CWA based analysis, three major texts (Vicente, 1999; Bisantz & Burns, 2009; Burns & Hajdukiewicz, 2004) and two major documents (Kilgore, St-Cyr & Jamieson, 2009; Miller & Vicente, 2001) were used as foundations. The structure of the chapter is in the following manner. First, the system formulation is presented. As the system formulation shows, the LOC device fabrication and testing have been separated into two phases. First phase 1 is addressed and then phase 2. Both these phases involve analysis related to CWA as well as WIDF. At the end of each of these phases, the requirements derived from the two sets are compared to each other.

5.2 System Formulation

The scope of the earlier chapter 4, was to understand the work activity related to the LOC device fabrication and testing in a research laboratory. The device was initially conceptualized based on the applications and principles of fluid dynamics at the small-scale. Next, the device was fabricated. In this fabrication phase, the work domain consists of various equipment and chemicals required to fabricate the chip from scratch. Once fabricated, the chip is tested in order to ascertain that it is functioning correctly. As described in chapter 4, this testing phase is conducted in a different section of the lab (section B) and the work domain of the testing phase is different from the fabrication phase; i.e., there are different equipment and entities involved in these two phases. To reflect the underlying reality of the LOC device’s fabrication and testing, two separate sets of models, corresponding to the two phases were created. In other words, for both CWA and WIDF, different models corresponding to the two phases (of fabrication and testing) were constructed.

5.3 Phase 1: Chip Fabrication

5.3.1 CWA approach

5.3.1.1 WDA

The first step in CWA is the work domain analysis. The following figure (AH 1.0, Figure 5.1), presents the abstraction hierarchy related to the chip fabrication. In AH 1.0, at the level of the functional purpose, there are two main purposes involved. First, based on the specifications, properly conceptualized chips; second, according to specifications correctly functioning chips. The next level of abstract functions includes conservation of mass for stoichiometric relations and the conservation laws of fluid dynamics. Both these entities are connected to the levels above; however, the conservation laws of fluid dynamics are not connected to the layer below. This is due to the reason that in conceptualizing the chip, the researchers take the laws into account. However, during the actual fabrication, the conservation laws of fluid dynamics laws do not affect the work domain. Researchers return to these conservation laws in the testing phase, to ascertain that the fabricated chips are functioning correctly. Since these conservation laws of fluid dynamics form the basis for conceptualizing the chips they are included in AH 1.0.

At the next level of generalized function, two main categories of processes exist. First, the chemical processes related to the creation of the master mold; second, the chemical and physical processes related to creating the LOC device. These processes instantiate the laws of the level of abstraction. These processes will be developed in detail in the work domain highlighting the causal representation during chip fabrication. The processes at the level of physical function involve the various components of the work domain and their capabilities. In this case, there are many equipment and chemicals present whose capabilities are required for the processes to exist in the work domain. For example, the UV light exposure system allows for the development of the silicon wafer. The lab, in which this study was conducted, had a UV exposure system with a 1000 W capacity. Another example of the entities of this level include silanizing agent. As discussed in chapter 4, the properties of the silanizing agent allows for the creation of bonding sites on PDMS; thus allowing for the creation of the chips from the molded PDMS and glass slides. Finally, at the level of physical form, the various characteristics and details of the devices are delineated. These include the spin coater specifications, the oxygen plasma setup as well as the different description of materials classifying them as solid, liquid or viscous liquids.

Along with the representation of the AH 1.0, a causal representation of the work domain is also present (AH 1.1, Figure 5.2). In this causal representation, the abstract functional level and the generalized functional level are developed in detail. At the abstract functional level, as described earlier in AH 1.0, there is a conservation of mass based on stoichiometric relations. Therefore, beginning with the initial mass, the mass undergoes transformations based on the chemical processes involved, resulting in the final mass. At the level of generalized function, as described earlier in AH 1.0, two main sets of processes exist. In terms of the chemical processes related to the master mold, the silicon wafer and chemicals, along with the process of etching provide a master mold and waste. The silicon wafer and chemicals are shown as dotted lines because they are not processes but intermediate products or resultants of the processes. They are presented in order to display the continuity between the different processes. The master mold is then used in the process of molding to generate a molded PDMS and waste. The molded PDMS, along with the PDMS-coated glass slide is used in the process of bonding to generate the LOC device. In this phase of fabrication, the whole system is considered as a single unit and not divided into subsystems. Since this phase does not allow for the strict demarcation between sub systems, the abstraction-decomposition space has not been developed for this phase.

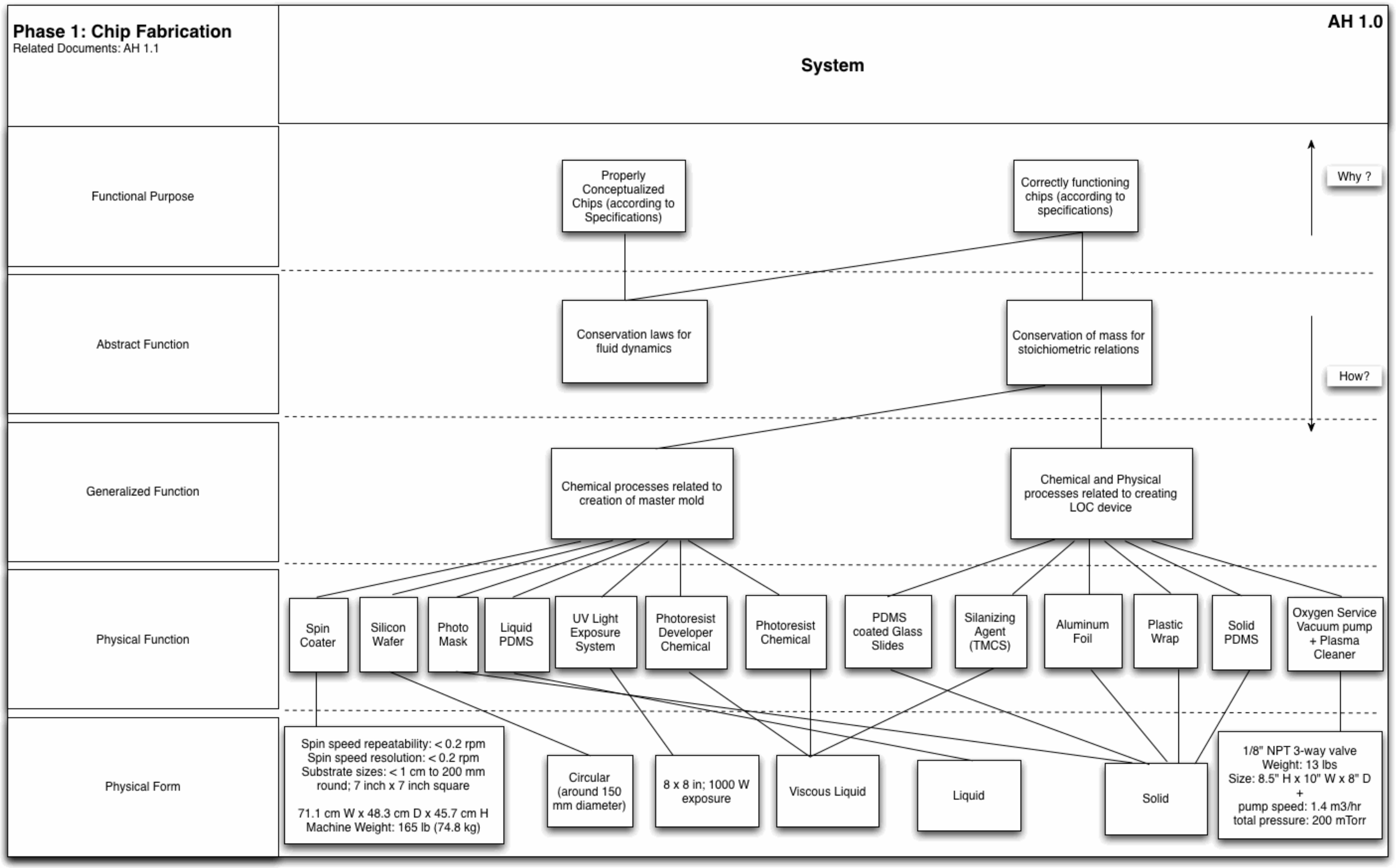


Figure 5.1: AH 1.0 for chip fabrication for phase 1

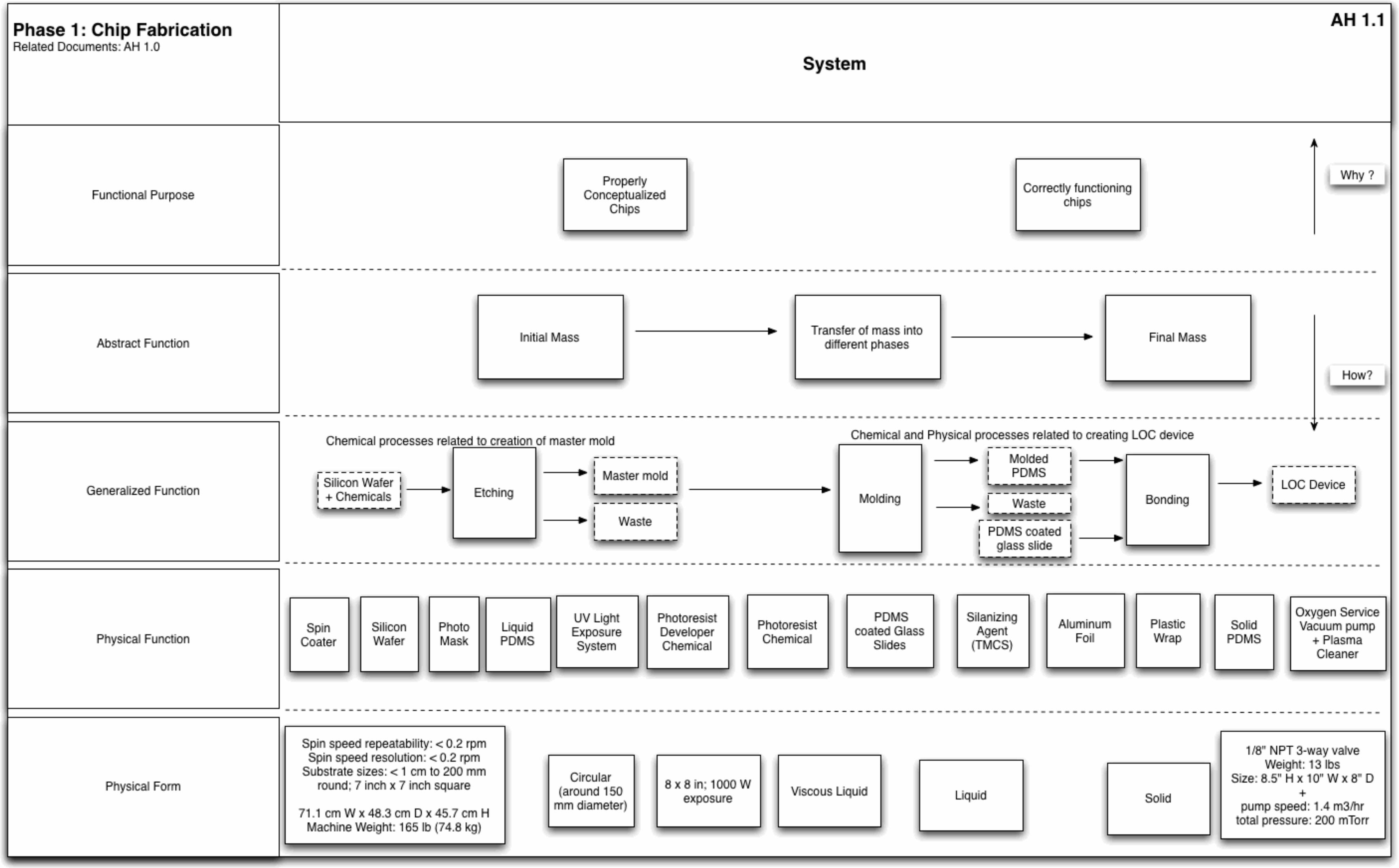


Figure 5.2: AH 1.1, Causal representation for chip fabrication for phase 1

5.3.1.2 ConTA

After the work domain, the next step of the CWA is to account for the control tasks related to the domain. The control task analysis identifies what needs to be done to achieve functional purpose of the domain. In the present case, a generalized control task of fabricating the LOC device is presented (DL 1.0, Figure 5.3; Table 5.1).

Control task analysis of making the LOC device-Decision Ladder **DL 1.0**

Related documents: AH 1.0

Number	Ladder Code	Notes	Type	Abstraction Level
1	Goal state	Conceptualize chips based on the research problem, along with the fact that they are correct functioning and according to specifications	Knowledge State	Functional Purpose, Abstract Function
2	Define Task	Define the associated tasks such as making master molds, molding, demolding, cutting of PDMS, forming a device	Information Processing Activity	Generalized function, Physical function
3	Task	A task state is formulated based on the various tasks involved in fabrication	Knowledge State	Generalized function, Physical function
4	Formulate procedures	A detailed set of procedures are formulated based on the number of tasks and the order in which they are to be executed	Information Processing Activity	Physical Function
5	Procedure	A set of procedures are formulated into a state based on the order in which they have to be executed along with the	Knowledge State	Physical Function, Physical Form

		individual details of the procedures		
6	Execute	Execute the planned procedures beginning with the first set	Activity	Physical Form
7	Observation	Observe information about the state of outcome of the procedure (for e.g. after making the master mold, observe whether the channels have been formed correctly)	Information Processing Activity	Generalized Function, Abstract Function
8	Set of Observations	Based on the observations from executing the procedures formulate a set of observations for the procedures	Knowledge State	Generalized function
9	Interpret	Based on the consequences related to the task efficiency and safety, interpret the set of observations. If ambiguities are present, evaluate observations in light of ultimate performance variables (higher steps)	Information Processing Activity	Generalized Function, Physical Function, Physical Form
10	Task	Reformulate the task of fabrication in light of the completed subtasks and goal state of completed chips	Knowledge State	Generalized function, Physical function

Table 5.1: Details for the Control task analysis for making LOC devices

Control task analysis of making LOC device - Decision Ladder **DL 1.0**

Related documents: AH 1.0

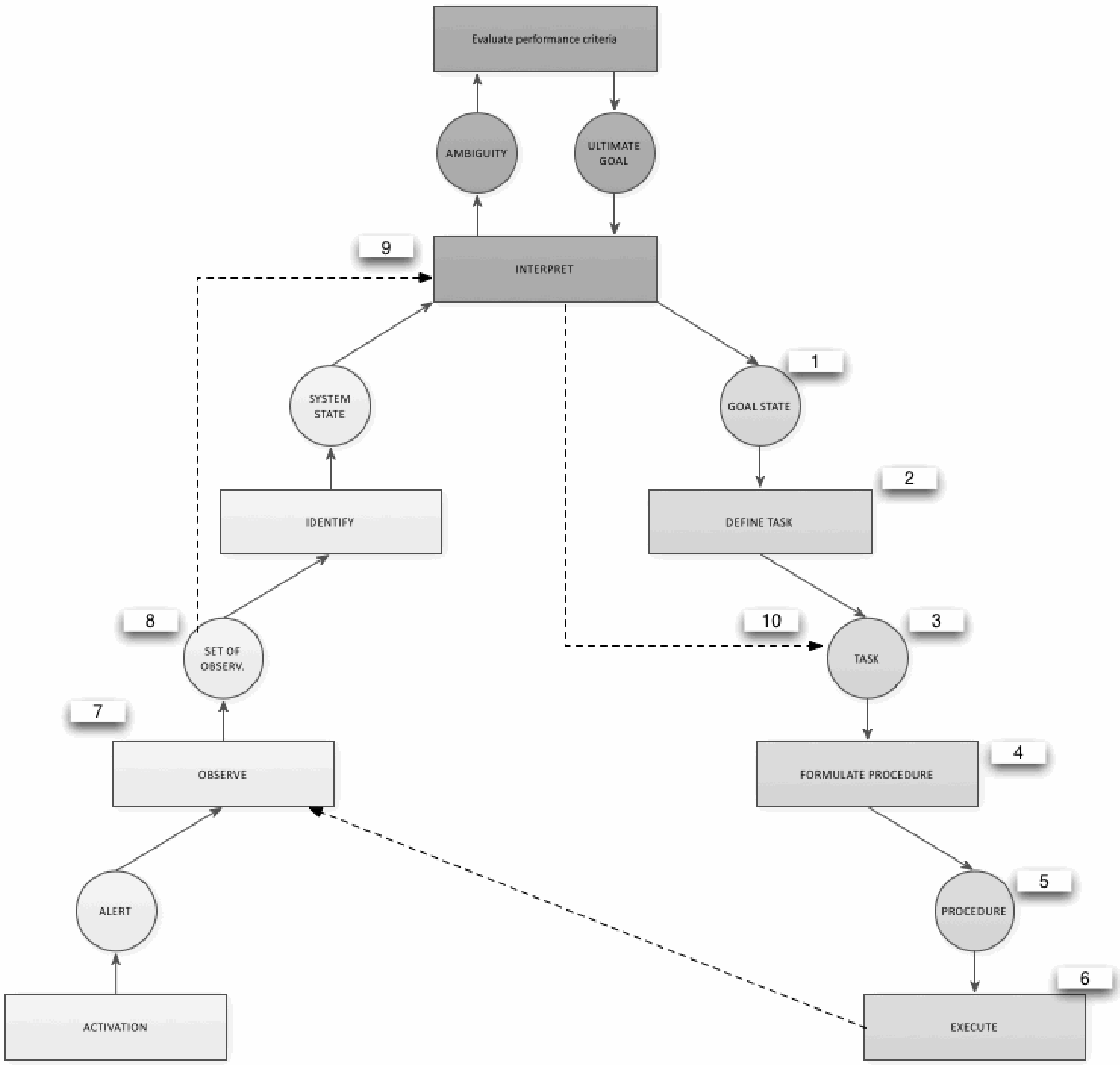


Figure 5.3: Decision Ladder for making LOC device

5.3.1.3 StrA

After the Control task analysis, a strategies analysis is conducted to understand, how the tasks are accomplished to achieve the functional goals of the system for the fabrication phase. In the present phase, there are four main strategies: strategies for aligning the glass slides on the table (Figure 5.4); strategies for spin coating on the turn table (Figure 5.5); strategies for cutting the PDMS block (Figure 5.6); strategies for joining the PDMS with the glass slide (Figure 5.7). Each of these strategies is discussed below in greater detail.

Strategies analysis for aligning the glass slide/wafer on the turn table StrA 1.1 Related documents: AH 1.0, DL 1.0	
1	The glass slide/wafer needs to be aligned properly on the turntable of the spin coater to ensure proper coating. The first strategy involves placing the glass slide centrally on the turntable and checking the placement visually to align the slide.
2	Another strategy for aligning the glass slide includes placing the glass slide on the table and rotating the turntable. After this step is done once or twice, the centrifugal force aligns the glass slide centrally
3	A third strategy for alignment includes placing the glass slide on the turntable and rotating the turntable. Next, observing one area of the turntable through which the end of the glass slide rotates. Then looking at the area that is at the antipode of the area previously looked at. Based on how the ends of the slide move, the decision is formulated about the alignment of the slide. If both ends of the antipodes pass through the areas of their opposite antipodes while rotating, then the slide is aligned centrally. If not, they are adjusted so that the central alignment is possible.

Table 5.2: Details of strategies analysis for aligning glass slide/wafer on the turn table

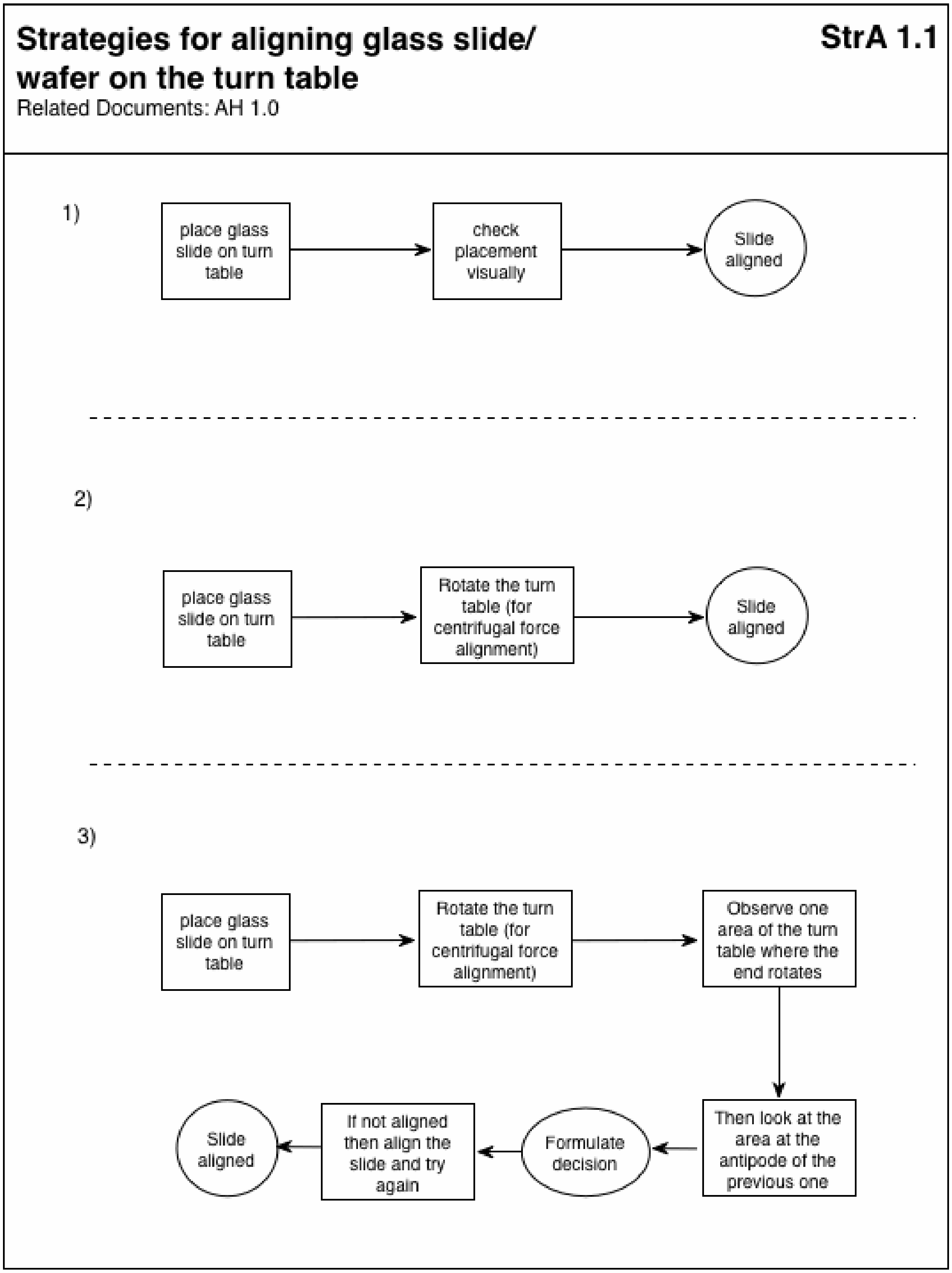


Figure 5.4: Strategies for aligning glass slide/wafer on the turntable

Strategies analysis for spin coating on the turn table Related documents: AH 1.0, DL 1.0	**StrA 1.2**
1	The first strategy involves pouring the PDMS in the middle of the slide. The next step involves rotating the turntable so that the centrifugal force spreads the PDMS on the glass to coat it thoroughly.
2	The second strategy involves pouring the PDMS in the middle of the tube in form of a large stretch of liquid and rotating the turntable. The large stretch allows for a move even coating on the slide.
3	The third strategy involves pouring the PDMS, in measured quantities, at three locations on the slide. Two spots are poured at the ends and these spots are connected by a thin line of PDMS. Once the PDMS is deposited, the turn table is rotated and the slide is spin coated

Table 5.3: Strategies for aligning the glass slide/ wafer on the turn table

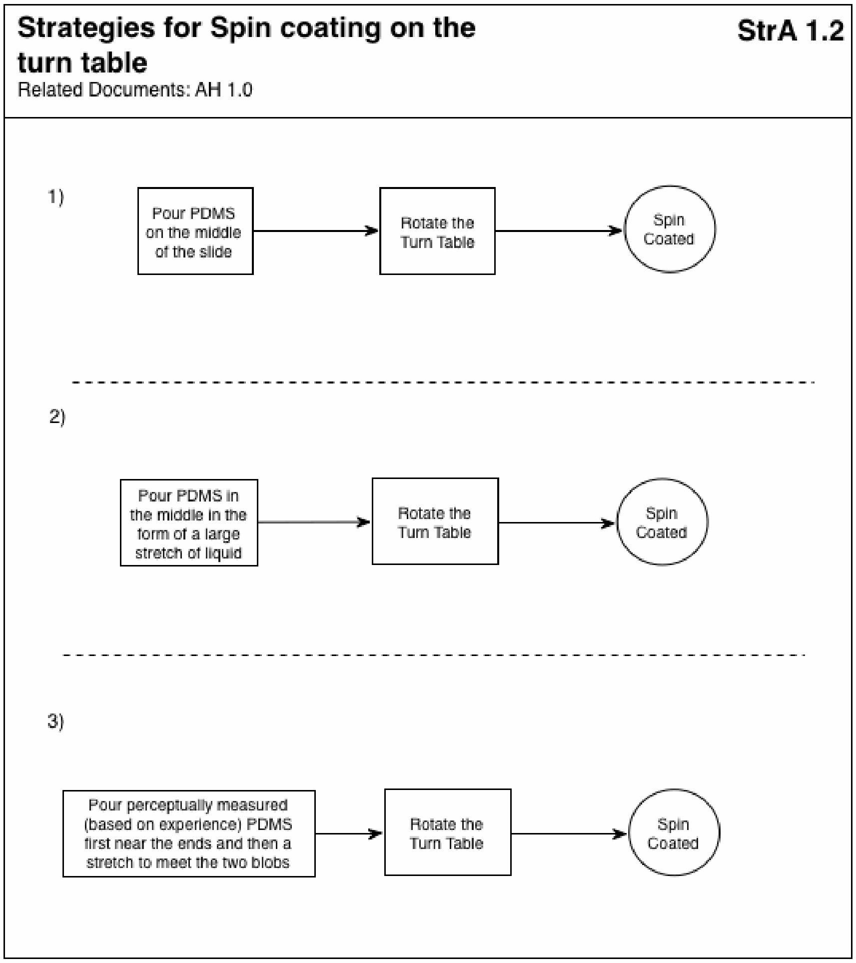


Figure 5.5: Strategies for spin coating on the turntable

Strategies analysis for cutting the PDMS blocks **StrA 1.3** Related documents: AH 1.0, DL 1.0	
1	For cutting the PDMS blocks, the first strategy employed is by placing the knife at the end of the PDMS block. The index finger of one hand is placed on the blunt edge of the knife while the other hand supports the PDMS. This setup mimics a chopping board. Once the setup is present, the knife supported by the finger for alignment is brought down to cut the knife and “chop” off the PDMS. The PDMS is cut into adequate strips.
2	The second strategy for cutting the PDMS involves sliding the knife on the PDMS to mimic a sawing motion. This motion is achieved by keeping both the knife and the PDMS block steady. If the knife and PDMS are not kept steady, then the resultant cut is not proper.

Table 5.4: Strategies for cutting the PDMS blocks

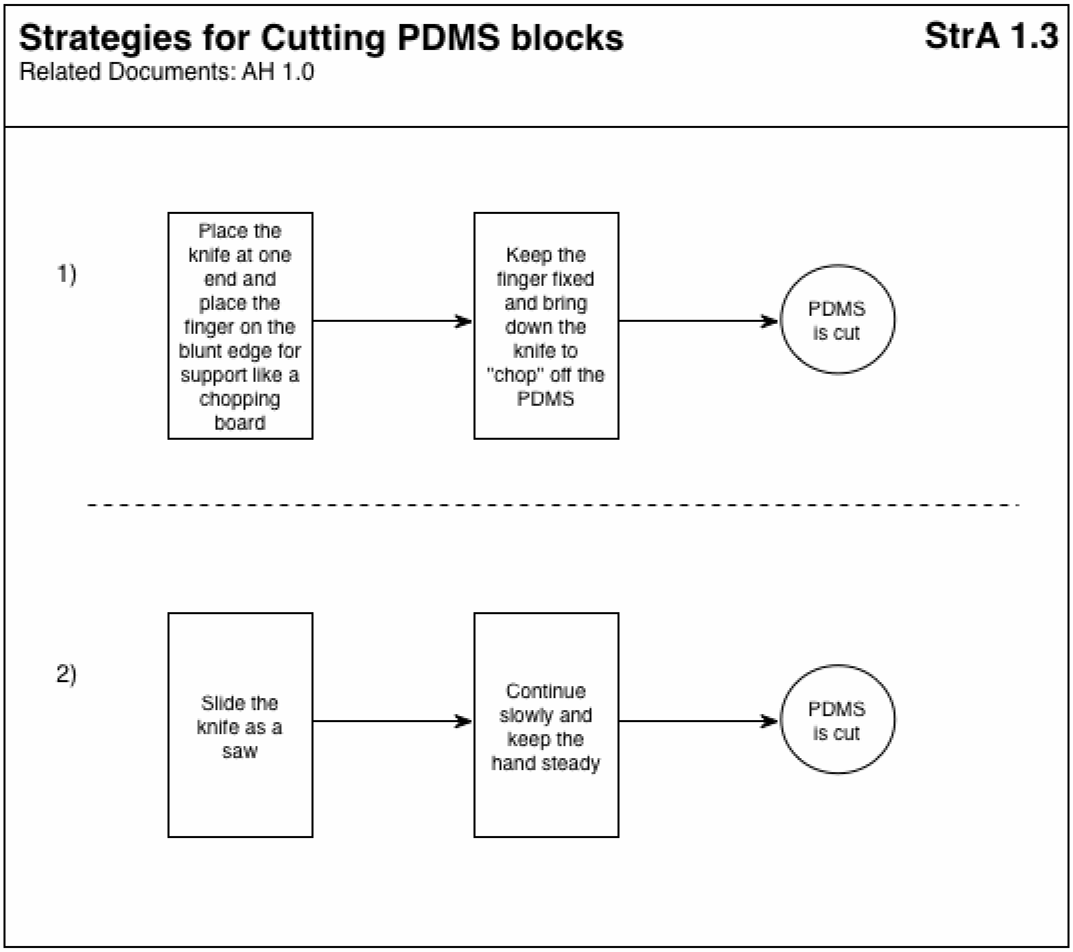


Figure 5.6: Strategies for cutting molded PDMS blocks

Strategies analysis for joining the PDMS with glass slide Related documents: AH 1.0, DL 1.0	**StrA 1.4**
1	The first strategy for bonding involves inserting the PDMS block, PDMS coated glass slide and silanol in plasma chamber. After this step, the wait time includes 7-8 seconds. After this wait time, the PDMS block and the glass slide are quickly stuck together to form the device.
2	The second strategy for bonding involves inserting the above mentioned contents in the plasma chamber. Then an idiosyncratic counting routine is followed by individual researchers. This counting routine is roughly equivalent to 7-8 seconds. Once the counting is over, the PDMS and glass slides are taken out and stuck together to form the chip.

Table 5.5: Details of the strategies for joining the PDMS with glass slides

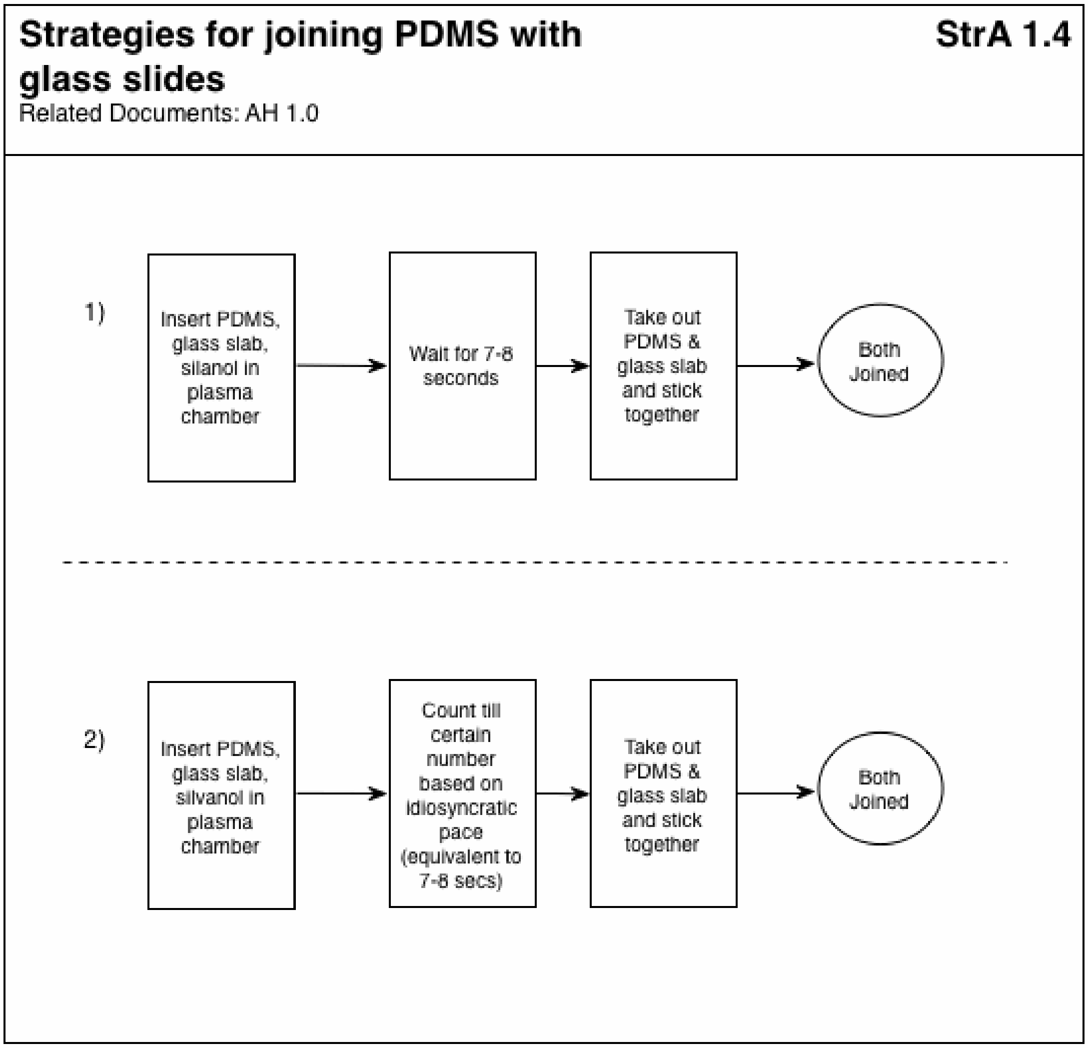


Figure 5.7: Strategies for joining the PDMS with a glass slide

5.3.1.4 WCA

The last analysis for CWA for phase 1 is the worker competency analysis (WCA). This WCA involves a discussion of the competencies of the researchers required for conducting the fabrication. In this analysis, the competencies required by the researchers are addressed. In terms of behavioral constraints related to the skills, rules and knowledge required for the associated work domain. The following figure (SRK 1.0, Table 5.6) represents the constraints related to skills, rules and knowledge categories for each information processing step and the associated knowledge state.

Worker Competencies Analysis **WCA 1.0**
Related documents: AH 1.0, DL 1.0

Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge- Based Behavior**
Associated Number	**Associated Number**			
	Goal state			Reasoning required to formulate a conceptual model of the LOC device on the basis of principles of fluid dynamics and the intended applications
	1			
Define Task	Task		Rules and heuristics required for various steps involved in the chip fabrication process	Reasoning required for formulating the tasks associated with chip fabrication. For example, the steps required for the tasks associated with creating master mold etc.
2	3			

Formulate procedures	Procedures	Perceptual-haptic knowledge required for each step of the overall fabrication. For e.g., perceptual-haptic skill required in cutting the PDMS, coating the glass slides etc.	Heuristics used for determining the optimal ways of conducting the tasks. For e.g. heuristics for pouring the material to ensure even coating of the slides, etc.	Knowledge required about the details of each procedure and how they have to be orchestrated are reasoned out in detail.
4	5			
Execute		Perceptual-haptic skill required for orchestrating the entire activity of the fabrication process	Heuristics involved in each step of the fabrication process to ensure proper outcomes	Knowledge of all the steps required to seamlessly execute the procedures
6				
Observation	Set of Observations	Monitoring of the appropriate signals for determining the next steps of the procedure	Use heuristics to decide whether the present step is complete in order to move on to the next step	In order for seamless switching to the next step in the list of procedures, prior knowledge of the steps are required for the overall procedure in order to execute it smoothly
7	8			

Interpret	Task	Once it is ascertained that a new task is required, automatic shifts are needed to shift from one task to the other	Use heuristics to ascertain the state of the task and ensure its completeness. For e.g. in the etching process, ascertain whether the grooves on the silicon wafer look even based on the past experiences with failures in etching	Based on reasoning of fundamental principles of chemistry reason out whether the processes have been executed properly. For e.g., in a few chips the chemical reactions were not taking place properly thus the development of the master mold was not proper.
9	10			

Table 5.6: Worker competencies analysis in the form of skills, rules and knowledge categories

5.3.2 WIDF approach

5.3.2.1 RCH Environment

The WIDF analysis can be started with the RCH for environment (RCH 1.1, Figure 5.8). As described earlier in chapter 3 of this thesis, four of the levels of RCH for environment resembles the AH; whereas, its last levels is derived from Rasmussen's original hierarchy. In the present case, the level of functional purpose contains two main purposes of the work domain: properly conceptualized chips and correctly functioning chips, based on the required specifications. At the next level of the abstract functions, the conservation of mass according to the stoichiometric relations are present along with the conservation of laws of fluid dynamics. The conservation laws of fluid dynamics are necessary for conceptualization of the chips and their correct functioning. However, the role of the laws of fluid dynamics does not play a major role in the actual chip fabrication and therefore, it is not connected to the level below it. However, these laws play a salient part in the testing process and are addressed in detail in the next phase.

The third level of the RCH consists of the chemical processes related to the creation of the master mold and the chemical and physical processes related to the creation of the device. The chemical processes related to the master mold require various equipment (e.g. spin coater) and chemicals (e.g. PDMS) for the entire process. Similarly, the creation of the device also entails several physical and chemical processes involving equipment (e.g. plasma pump) and chemicals (e.g. TMCS). The next level of physical form describes the various characteristics, specifications and details of the equipment and related chemicals. For example, descriptions include the specifications of the spin coater as well as the plasma setup. Along with these above layers, the final layer of the RCH consists of the use values (or affordances). In the present case, settings of the various equipment afford a certain outcome; i.e., the settings allow for the proper use of the device for the chip fabrication. Next, along with the equipment, the properties of the materials hamper or aid in the creation of the device. In other words, they affect the workability of the materials. Therefore, the solid PDMS allows cutting but at the same time due to its jello-like nature also provides resistance. Therefore, the materials and chemicals afford certain properties that enable certain activities for the completion of the device. Further, some properties of the chemicals can be hazardous to the health (e.g. TMCS). Therefore, these chemicals should be used in a manner to avoid close contact. Since not all chemicals and materials are hazardous (e.g. PDMS), the line connecting the entity of the properties to the layer above is represented as dashed.

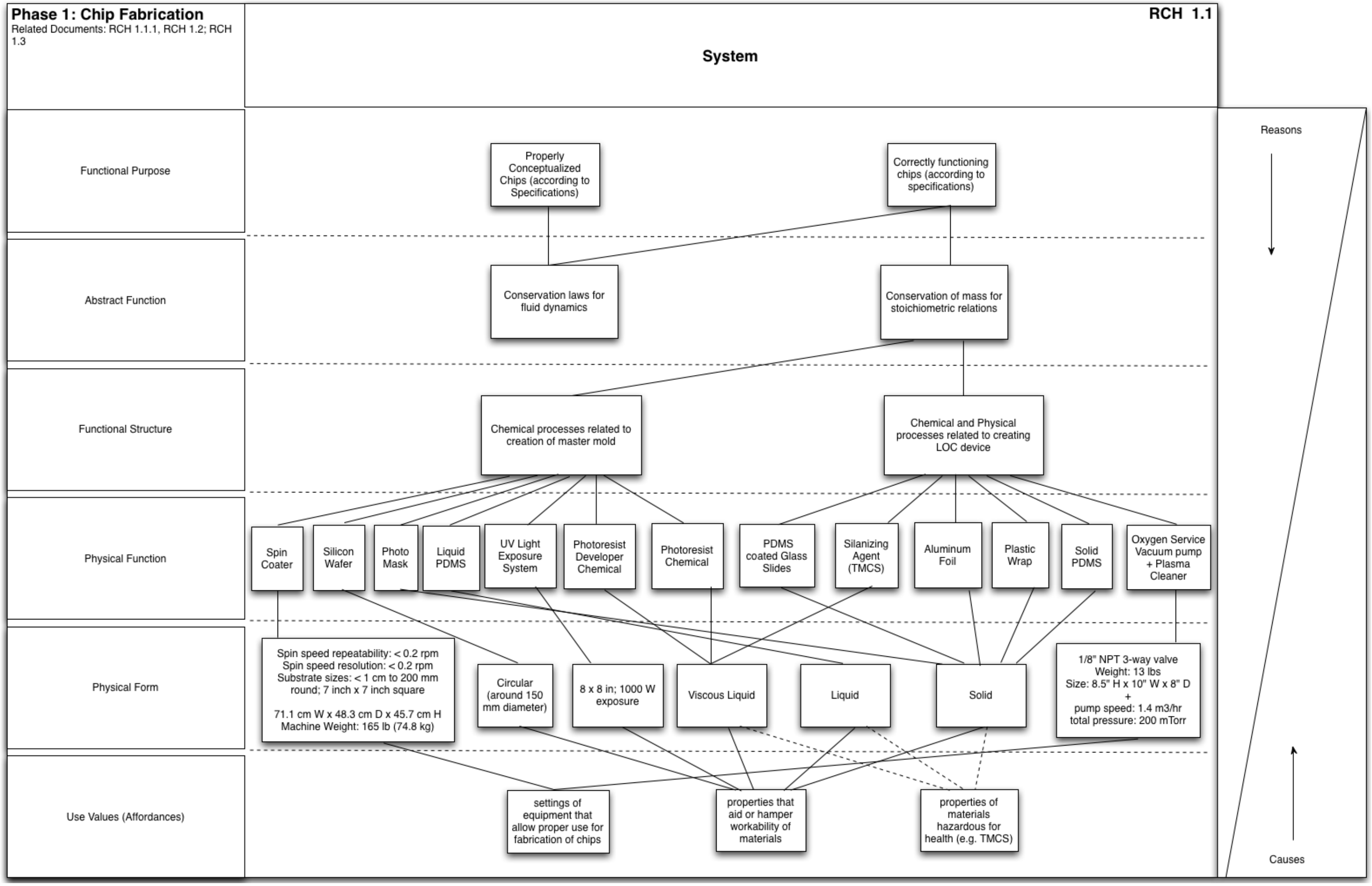


Figure 5.8: RCH environment for chip fabrication for phase 1

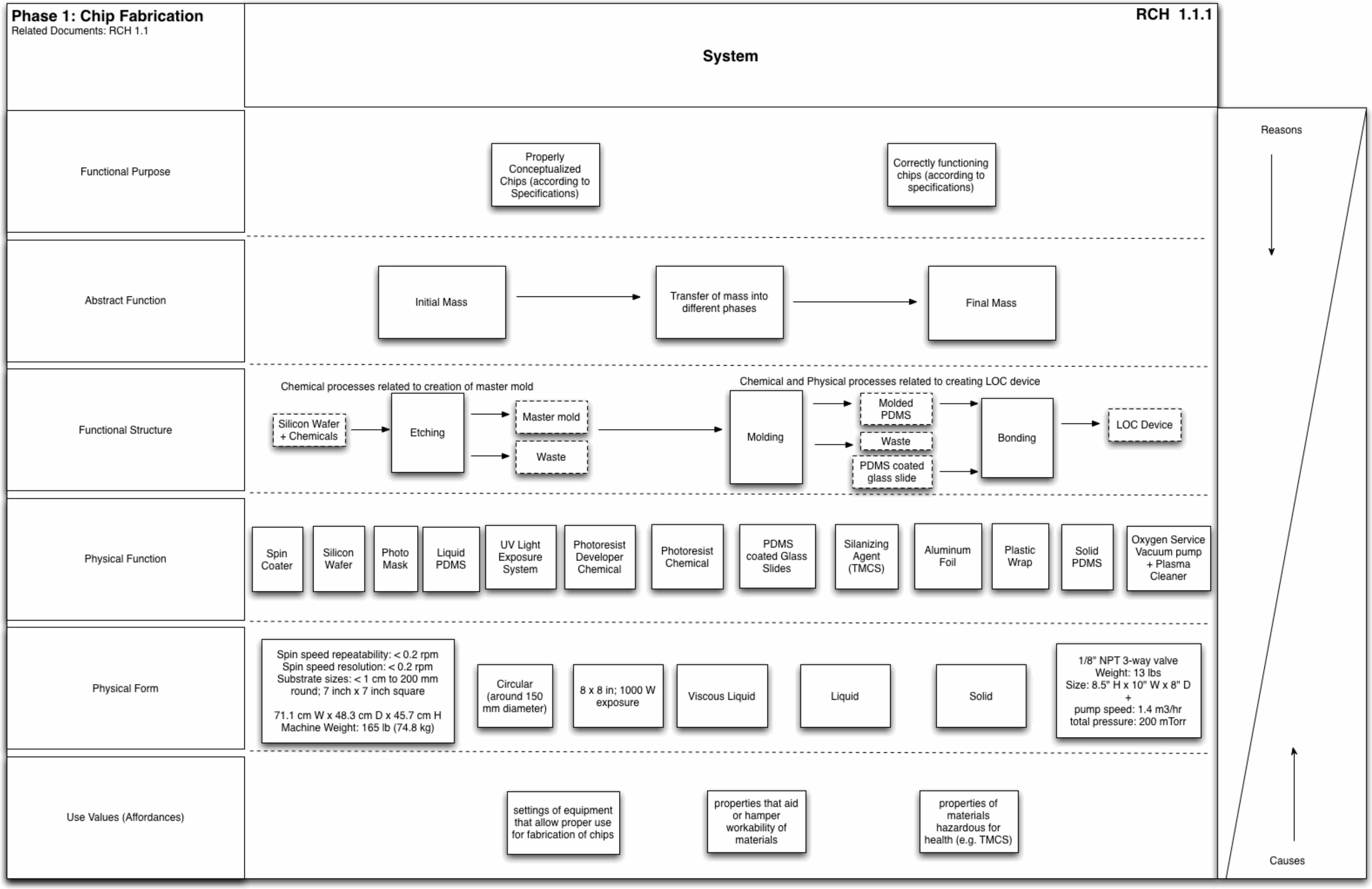


Figure 5.9: Causal representation for RCH scene for chip fabrication for phase 1

Along with the representation of RCH 1.1, a causal representation of the work domain is also present (RCH 1.1.1,Figure 5.9). In this causal representation, the level of abstract function and generalized function are developed in detail. At the level of abstract function there is the conservation of mass based on stoichiometric relations. Therefore, beginning with the initial mass, the mass undergoes transformation and in the end, produces the final mass. The level of abstract function is instantiated by generalized function in which the silicon wafer produces the master mold by the process of etching. The master mold is then used to make solid PDMS by the process of molding. The molded PDMS is cut into strips and through the process of bonding linked with the glass slide to produce the final chip. Further, since this phase does not allow for the strict demarcation between sub systems, the abstraction-decomposition space has not been developed for this phase.

5.3.2.2 RCH Agent

In case of RCH for agents (RCH 1.2, Figure 5.10), the first layer corresponds to the intentions and presents two overlapping intentions. First, the chips have to conceptualize according to the research agenda as well as the required specifications. Second, the fabrication of the device should be such that the devices work correctly and according to specifications. At the next level of abstract function relating to the psychological laws/ physiological laws, the present domain requires an understanding of the perception-action relations that are present throughout the phase of the device creation. In the next level, the physiological and psychological mechanisms are salient. The mechanisms at this level appear in the form of decision making of the proper course of activity, given the materials and equipment setup. Along with decision making, the mechanisms of visual and haptic perception are involved that allow tasks such as pouring the PDMS and for proper spin coating. Further, attentional processes also occur throughout the phase of the chip fabrication. In particular cases such as alignment of the glass slide on the spin coater, requires a heavy demand on attention. Further, the mechanisms involved in haptic perception are also salient especially in making precision cuts on the molded PDMS.

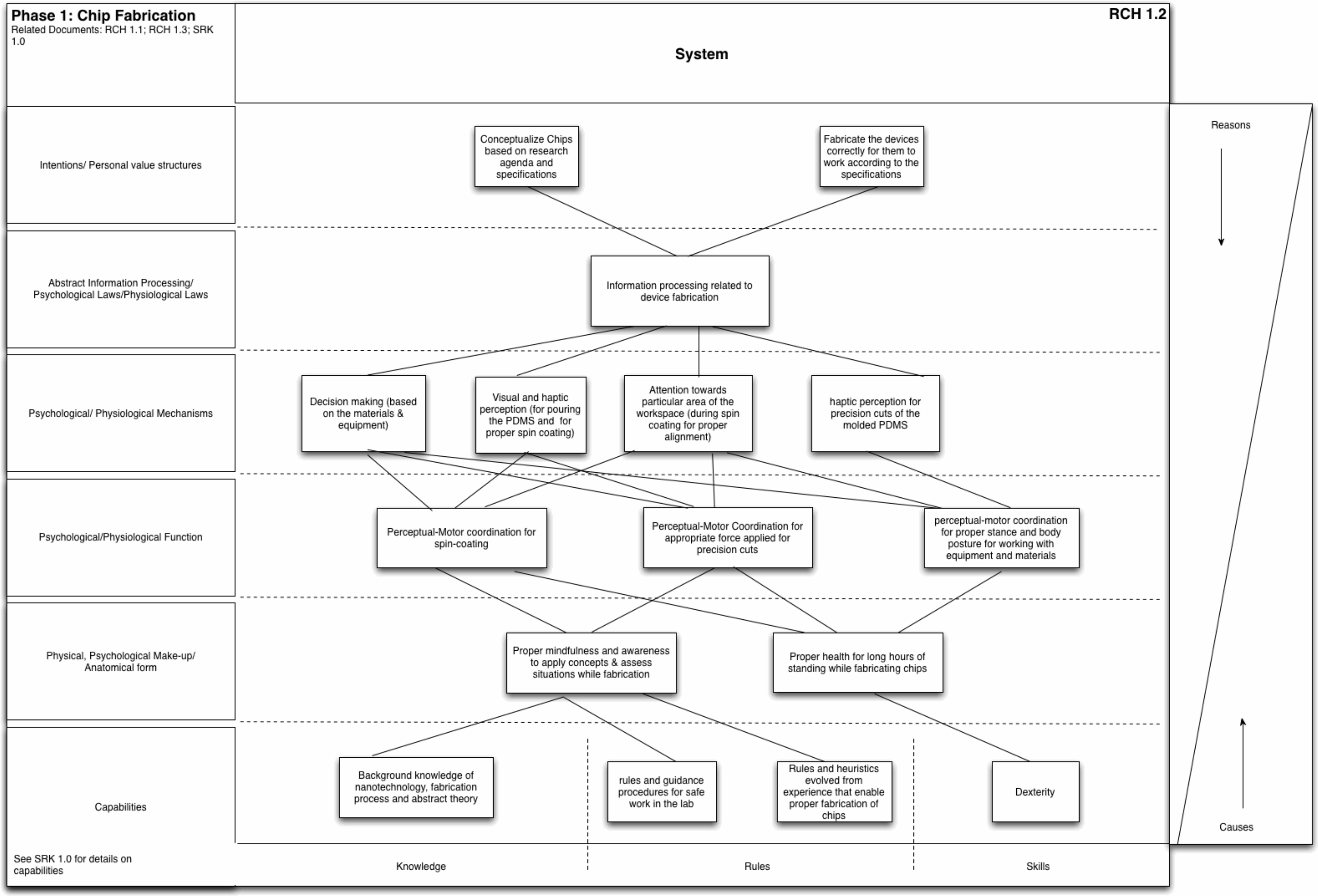


Figure 5.10: RCH Agent for chip fabrication for Phase 1

At the next level of psychological/ physiological function, the perceptual motor-coordination allows for seamless activities. For example, perceptual-motor coordination is required for spin coating, as well as, for providing appropriate force during the formation of precision cuts to the PDMS. Further, perceptual-motor coordination is also required for proper stance of the body and posture during working with the equipment and materials. At the level of the physical, psychological make-up/ anatomical form, there is a need for proper mindfulness and awareness to apply the concepts of nanotechnology to the fabrication of the chips as well as assess situations while fabrication. Further, proper health is required for the long hours of standing while fabricating the chips. Finally, at the lowest level, the capabilities of the individual are divided into skills, rules and knowledge. At the level of skills, the researcher requires dexterity to manipulate the materials in order to form the chips. In terms of rules, guidance procedures for working safely in the laboratory are already present in this domain. Researchers are provided training before they begin work in the laboratory. Further, in the process of creating chips, researchers formulate rules and heuristics based on experience that enable them to successfully create properly working chips. Along with the rules, researchers should possess background knowledge of nanotechnology in terms of abstract theory as well as concrete procedures related to fabrication. The capabilities in the form of the SRK taxonomy have been developed further in SRK 1.0 (Table 5.7). In this taxonomy, detailed skills, rules, and knowledge, required by the researchers for the fabrication of chips, is expressed in greater detail. Further since there is only one kind of agent, i.e., LOC researchers, involved in a set of activities, the abstraction decomposition space has not been developed for RCH-Person and RCH-Acts for Phase 1 or Phase 2.

Skills, Rules and Knowledge Taxonomy				**SRK 1.0**
Related documents: RCH 1.1, RCH 1.2				
Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge- Based Behavior**

Associated Number	**Associated Number**			
	Goal state			Reasoning required to formulate a conceptual model of the LOC device on the basis of principles of fluid dynamics and the intended applications
	1			
Define Task	Task		Rules and heuristics required for various steps involved in the chip fabrication process	Reasoning required for formulating the tasks associated with chip fabrication. For example, the steps required for the tasks associated with creating master mold etc.
2	3			
Formulate procedures	Procedures	Perceptual-haptic knowledge required for each step of the overall fabrication. For e.g., perceptual-haptic skill required in cutting the PDMS, coating the glass slides etc.	Heuristics used for determining the optimal ways of conducting the tasks. For e.g. heuristics for pouring the material to ensure even coating of the slides, etc.	Knowledge required about the details of each procedure and how they have to be orchestrated are reasoned out in detail.
4	5			
Execute		Perceptual-haptic skill required for orchestrating the entire activity of the fabrication process	Heuristics involved in each step of the fabrication process to ensure proper outcomes	Knowledge of all the steps required to seamlessly execute the procedures
6				

Observation	Set of Observations	Monitoring of the appropriate signals for determining the next steps of the procedure	Use heuristics to decide whether the present step is complete in order to move on to the next step	In order for seamless switching to the next step in the list of procedures, prior knowledge of the steps are required for the overall procedure in order to execute it smoothly
7	8			
Interpret	Task	Once it is ascertained that a new task is required, automatic shifts are needed to shift from one task to the other	Use heuristics to ascertain the state of the task and ensure its completeness. For e.g. in the etching process, ascertain whether the grooves on the silicon wafer look even based on the past experiences with failures in etching	Based on reasoning of fundamental principles of chemistry reason out whether the processes have been executed properly. For e.g., in a few chips the chemical reactions were not taking place properly thus the development of the master mold was not proper.
9	10			

Table 5.7: Skills, Rules, knowledge taxonomy describing the capabilities of the agent for chip fabrication of phase 1

5.3.2.3 RCH Act

Along with the other two reason-causes hierarchies, the third RCH addresses the acts involved in the LOC device fabrication (RCH 1.3, Figure 5.11). At the first level, the symbolic purpose of the acts is to devise a chip, which is properly conceptualized and also properly fabricated. At the next level of abstract information processing/meaning processing activities, the states and activities related to the processing are addressed. As discussed in chapter 3, this layer can be developed further in terms of understanding the details of the information processing activities. Thus, the decision ladder is used to develop the information processing activities involved in creating the chip (RCH 1.3-DL 1.3.1, Figure 5.12).

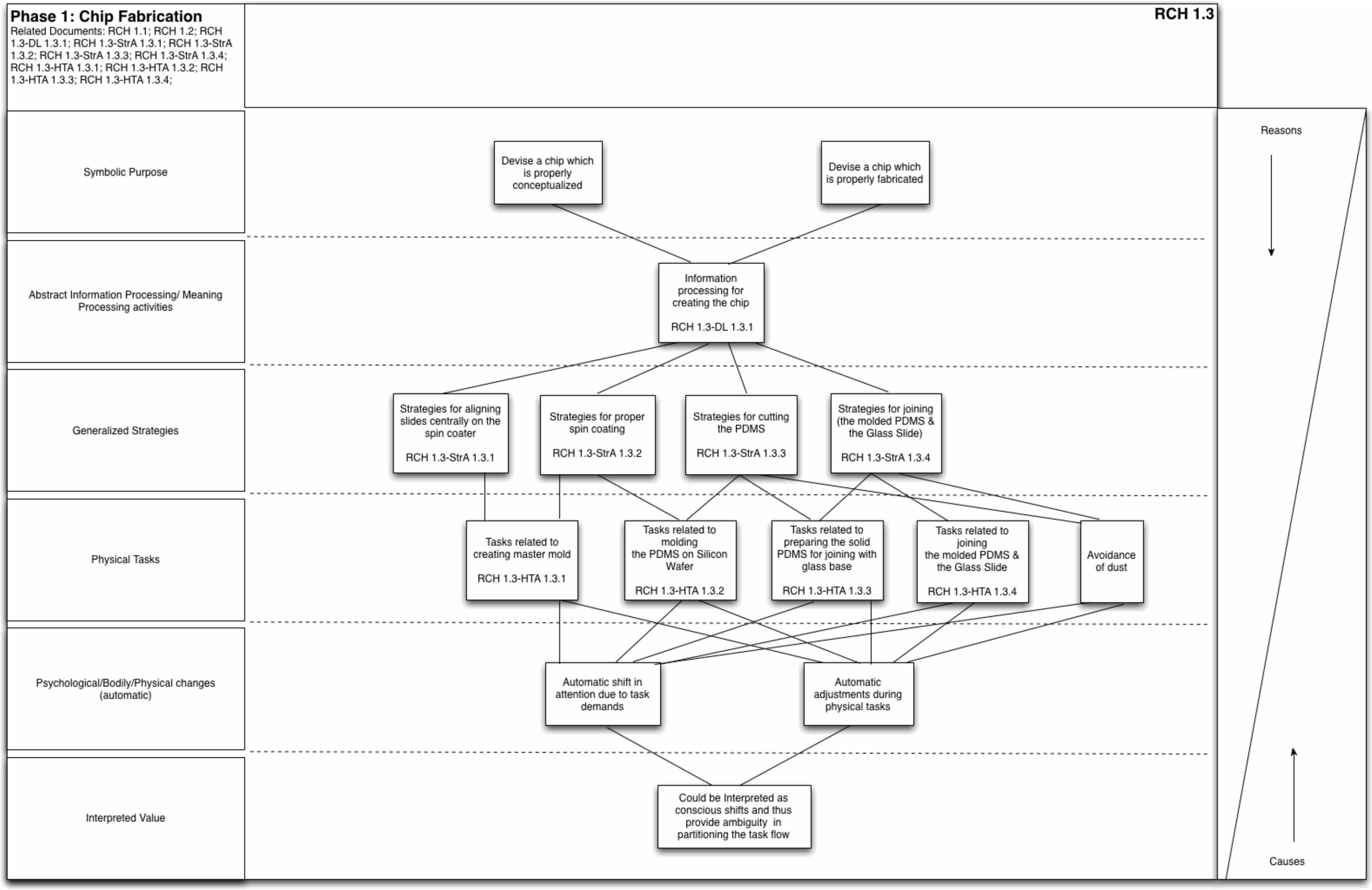


Figure 5.11: RCH Act for chip fabrication for phase 1

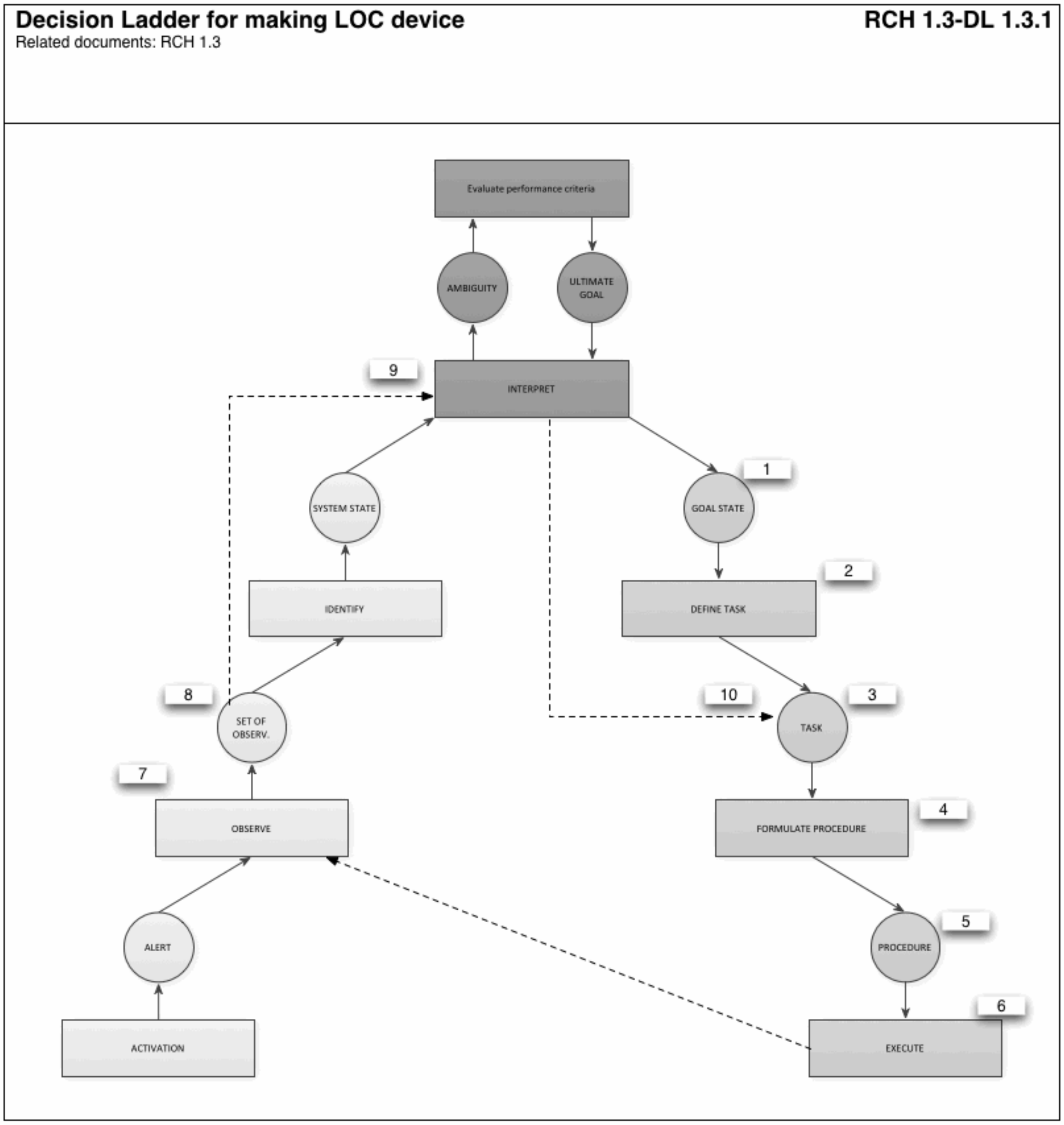


Figure 5.12: Decision ladder associated with the information processing activities of RCH Act

Decision Ladder for making the LOC device Related documents: AH 1.0				**DL 1.0**
Number	**Ladder Code**	**Notes**	**Type**	**Abstraction Level**
1	Goal state	Conceptualize chips based on the research problem, along with the fact that they are correct functioning and according to specifications	Knowledge State	Functional Purpose, Abstract Function
2	Define Task	Define the associated tasks such as making master molds, molding, demolding, cutting of PDMS, forming a device	Information Processing Activity	Generalized function, Physical function
3	Task	A task state is formulated based on the various tasks involved in fabrication	Knowledge State	Generalized function, Physical function
4	Formulate procedures	A detailed set of procedures are formulated based on the number of tasks and the order in which they are to be executed	Information Processing Activity	Physical Function
5	Procedure	A set of procedures are formulated into a state based on the order in which they have to be executed along with the individual details of the procedures	Knowledge State	Physical Function, Physical Form
6	Execute	Execute the planned procedures beginning with the first set	Activity	Physical Form
7	Observation	Observe information about the state of outcome of the procedure (for e.g.	Information Processing Activity	Generalized Function, Abstract Function

		after making the master mold, observe whether the channels have been formed correctly)		
8	Set of Observations	Based on the observations from executing the procedures formulate a set of observations for the procedures	Knowledge State	Generalized function
9	Interpret	Based on the consequences related to the task efficiency and safety, interpret the set of observations. If ambiguities are present, evaluate observations in light of ultimate performance variables (higher steps)	Information Processing Activity	Generalized Function, Physical Function, Physical Form
10	Task	Reformulate the task of fabrication in light of the completed subtasks and goal state of completed chips	Knowledge State	Generalized function, Physical function

Table 5.8: Decision ladder for making the LOC device

At the third level of acts in RCH Act (RCH 1.3), the generalized strategies relating to the activities of the work domain are addressed. These include strategies for aligning the glass slides on the spin coater (RCH 3.0-StrA 1.3.1, Figure 5.13); strategies for spin coating (RCH 3.0-Str 1.3.2, Figure 5.14); strategies for cutting the PDMS (RCH 3.0-Str 1.3.3, Figure 5.15) and strategies for creating the chip by bonding PDMS and the glass slide (RCH 3.0-Str 1.3.4, Figure 5.16). As described in chapter 3, the strategies can be developed further in terms of information flow maps; here the various strategies have been developed further.

Strategies analysis for aligning the slide/wafer on the turn table	**RCH 3.0-StrA 1.3.1**
Related documents: AH 1.0, DL 1.0	
1	The glass slide/wafer needs to be aligned properly on the turntable of the spin coater to ensure proper coating. The first strategy involves placing the glass slide centrally on the turntable and checking the placement visually to align the slide.
2	Another strategy for aligning the glass slide includes placing the glass slide on the table and rotating the turntable. After this step is done once or twice, the centrifugal force aligns the glass slide centrally.
3	A third strategy for alignment includes placing the glass slide on the turntable and rotating the turntable. Next, observing one area of the turntable through which the end of the glass slide rotates. Then looking at the area that is at the antipode of the area previously looked at. Based on how the ends of the slide move, the decision is formulated about the alignment of the slide. If both ends of the antipodes pass through the areas of their opposite antipodes while rotating, then the slide is aligned centrally. If not, they are adjusted so that the central alignment is possible.

Table 5.9: Details of strategies analysis for aligning the slide/wafer on the turntable

Strategies analysis for spin coating on the turn table	**RCH 3.0-StrA 1.3.2**
Related documents: AH 1.0, DL 1.0	
1	The first strategy involves pouring the PDMS in the middle of the slide. The next step involves rotating the turntable so that the centrifugal force spreads the PDMS on the glass to coat it thoroughly.
2	The second strategy involves pouring the PDMS in the middle of the tube in form of a large stretch of liquid and rotating the turntable. The large stretch allows for a move even coating on the slide.
3	The third strategy involves pouring the PDMS, in measured quantities, at three locations on the slide. Two spots are poured at the ends and these spots are connected by a thin line of PDMS. Once the PDMS is deposited, the turn table is rotated and the slide is spin coated

Table 5.10: Details for Strategies of spin coating on the turntable

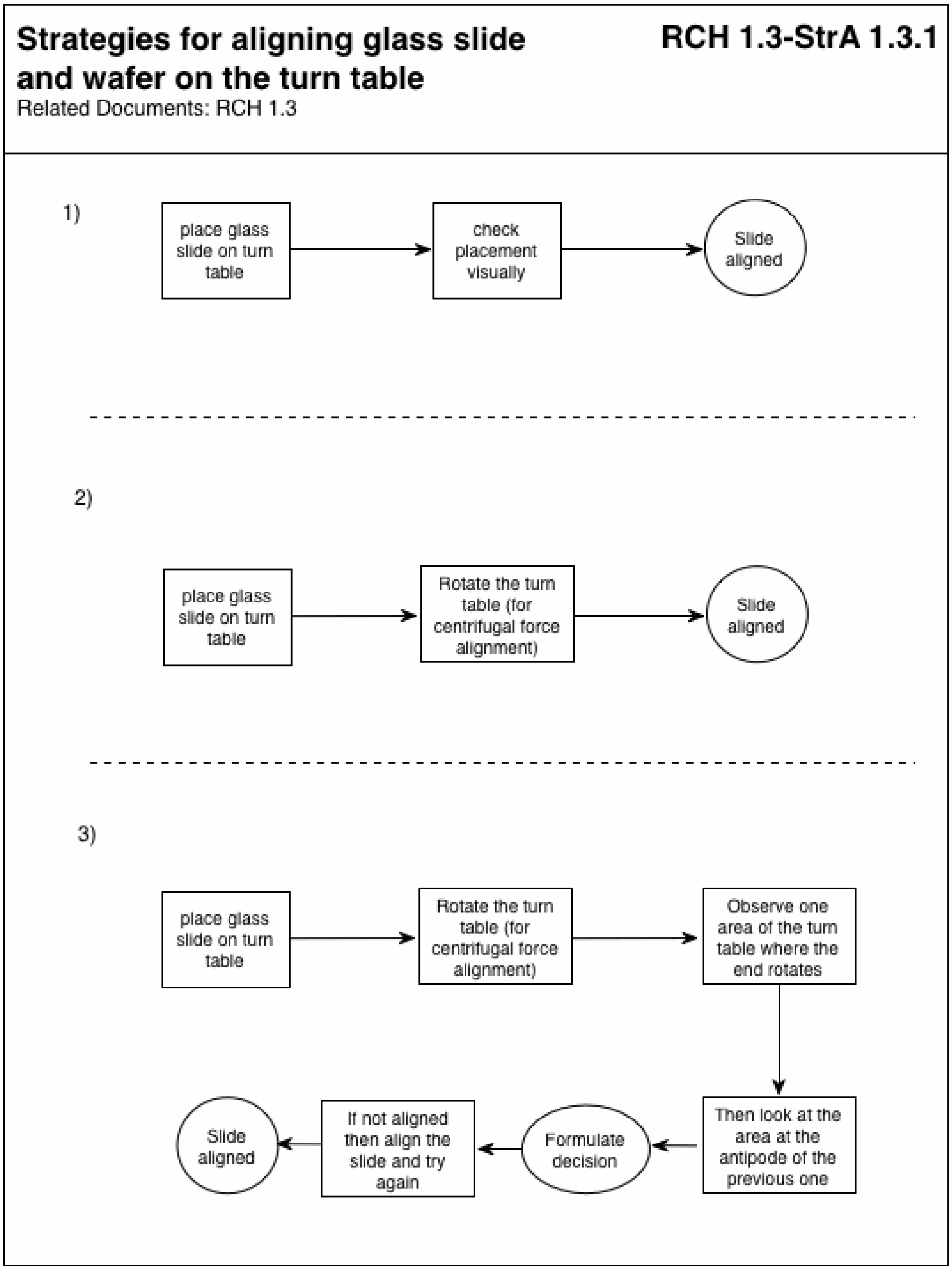


Figure 5.13: Strategies for aligning glass slides and wafers on the turntable of spin coater

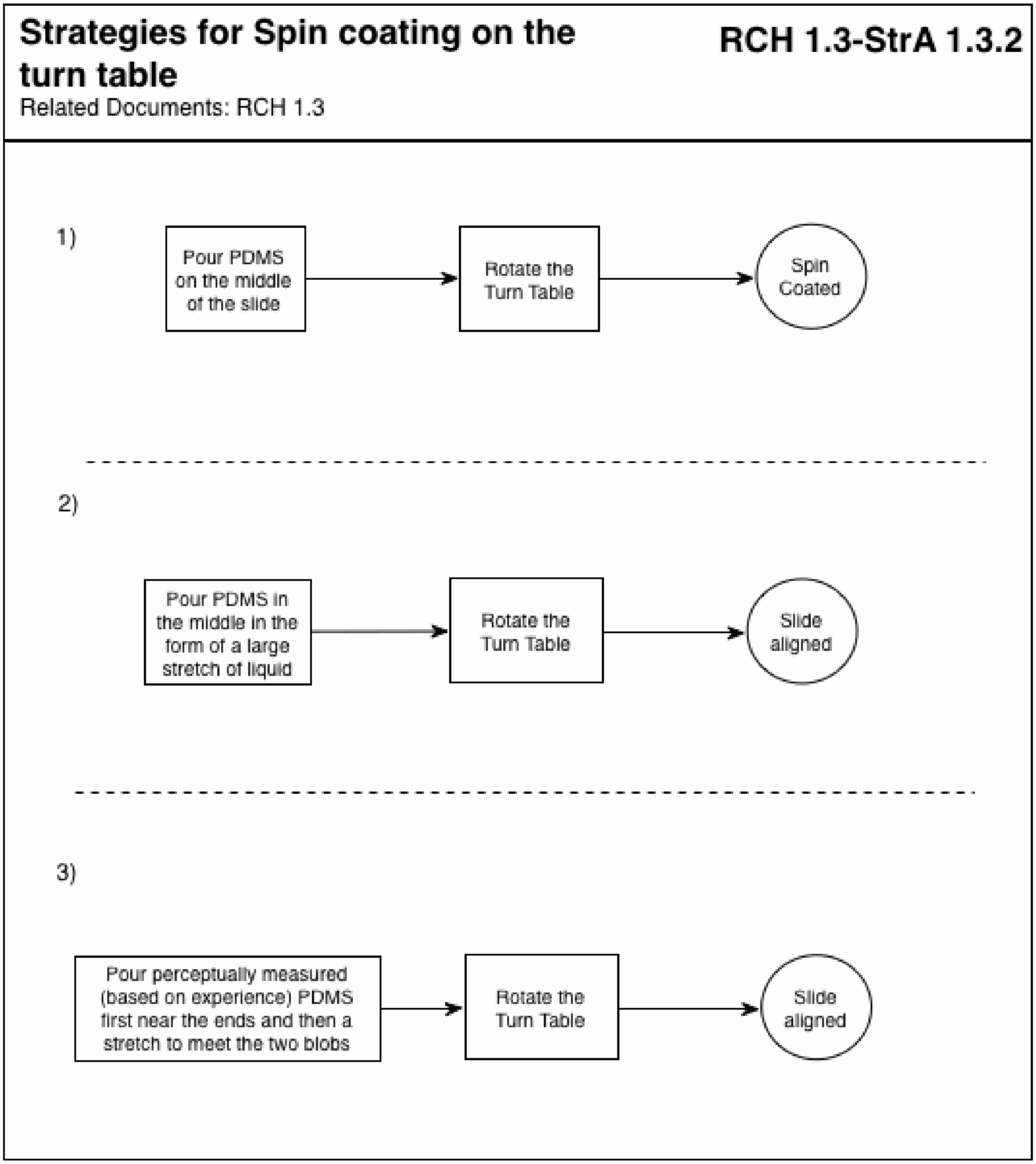


Figure 5.14: Strategies for spin coating on the turntable

<table>
<tr><td colspan="2">Strategies analysis for cutting the PDMS blocks RCH 3.0-StrA 1.3.3
Related documents: AH 1.0, DL 1.0</td></tr>
<tr><td>1</td><td>For cutting the PDMS blocks, the first strategy employed is by placing the knife at the end of the PDMS block. The index finger of one hand is placed on the blunt edge of the knife while the other hand supports the PDMS. This setup mimics a chopping board. Once the setup is present, the knife supported by the finger for alignment is brought down to cut the knife and “chop” off the PDMS. The PDMS is cut into adequate strips.</td></tr>
<tr><td>2</td><td>The second strategy for cutting the PDMS involves sliding the knife on the PDMS to mimic a sawing motion. This motion is achieved by keeping both the knife and the PDMS block steady. If the knife and PDMS are not kept steady, then the resultant cut is not proper.</td></tr>
</table>

Table 5.11: Strategies for cutting the PDMS blocks

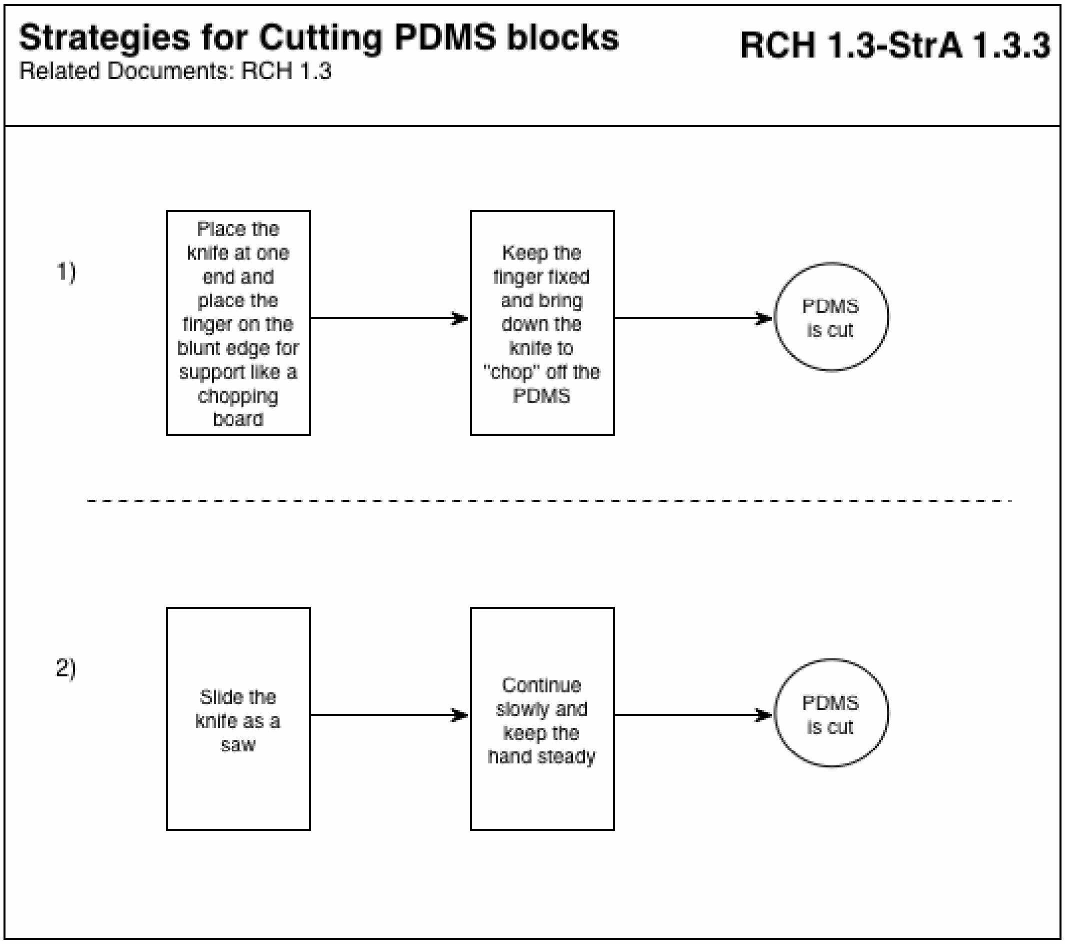


Figure 5.15: Strategies for cutting PDMS blocks

Strategies analysis for joining the PDMS with glass slide Related documents: AH 1.0, DL 1.0	**RCH 3.0-StrA 1.3.4**
1	The first strategy for bonding involves inserting the PDMS block, PDMS coated glass slide and silanol in plasma chamber. After this step, the wait time includes 7-8 seconds. After this wait time, the PDMS block and the glass slide are quickly stuck together to form the device.
2	The second strategy for bonding involves inserting the above mentioned contents in the plasma chamber. Then an idiosyncratic counting routine is followed by individual researchers. This counting routine is roughly equivalent to 7-8 seconds. Once the counting is over, the PDMS and glass slides are taken out and stuck together to form the chip.

Table 5.12: Strategies for joining the PDMS with glass slide

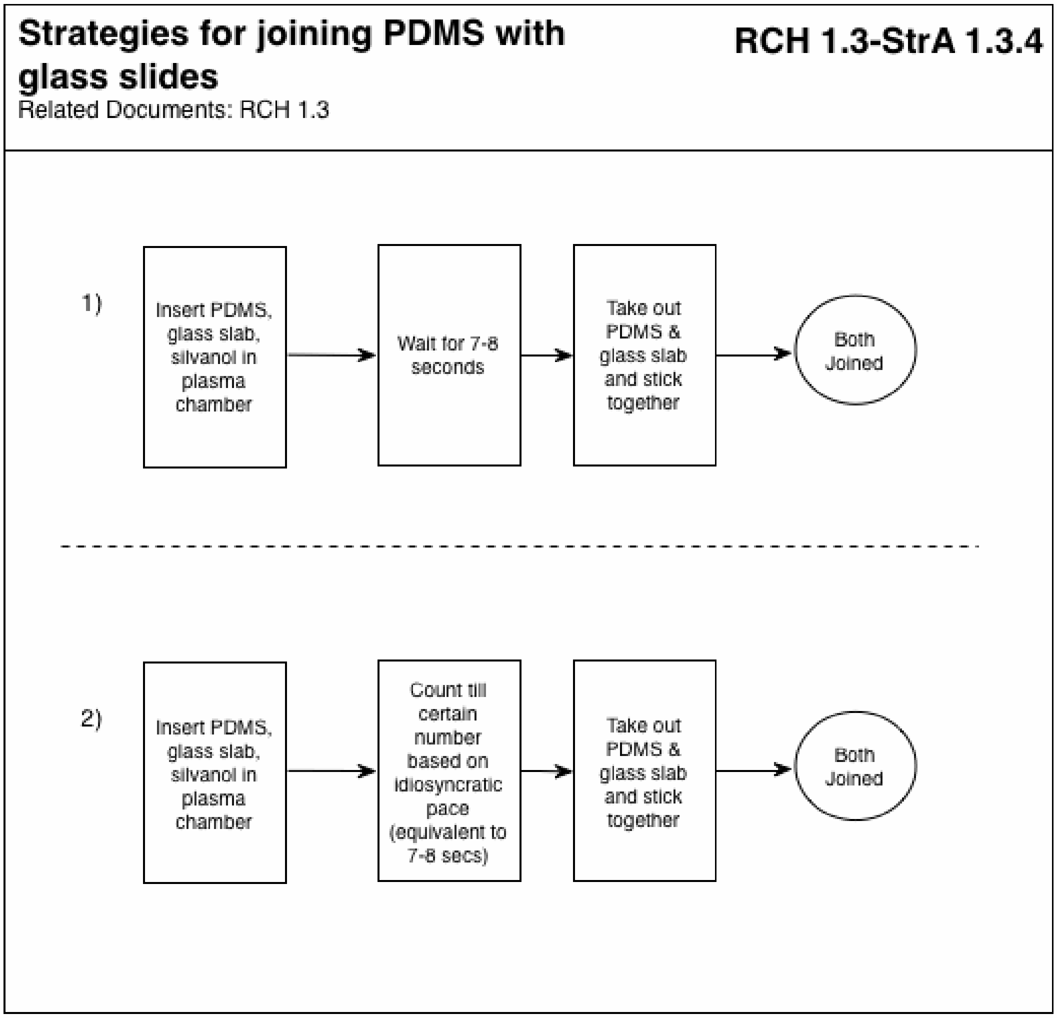


Figure 5.16: Strategies for joining PDMS with a glass slide

The next level of physical task describes the various tasks in terms of how they interrelate to provide a unified understanding of the act. As described in chapter 3, this level of physical tasks can be developed further in terms of hierarchical task analysis. Therefore, in the present case, the tasks are developed further as follows. In the present case the various tasks associated at this level include tasks related to creation of master mold (RCH-HTA 1.3.1, Figure 5.17); tasks related to the molding of PDMS (RCH-HTA 1.3.3, Figure 5.18); tasks related to the preparing the solid PDMS for joining to the glass base (RCH-HTA 1.3.4, Figure 5.19); and tasks related to joining the molded PDMS to the glass slide (RCH-HTA 1.3.5, Figure 5.20). Further, there is also an avoidance of dust in the fabrication of the chip. Since the avoidance of dust is present in all the major tasks related to the fabrication, it is not elaborated in detail by any specific set of tasks.

After the level of physical tasks, the level of the bodily/physical changes accounts for the automatic processes related to the acts. Thus, at any given time, there are automatic shifts in attention, to suit the demands of the workspace as well as automatic adjustments during physical tasks. These automatic changes are seamlessly integrated into the overall flow of activity in the chip fabrication. As a result, these acts can be interpreted, by others, in terms of conscious and intentional shifts. Thus, the task flow can become ambiguous in nature and may pose a challenge in terms of proper partitioning of tasks by an external observer. After the three RC hierarchies are described, the design requirements elicited by both CWA and WIDF are compared to each other (Table 5.13).

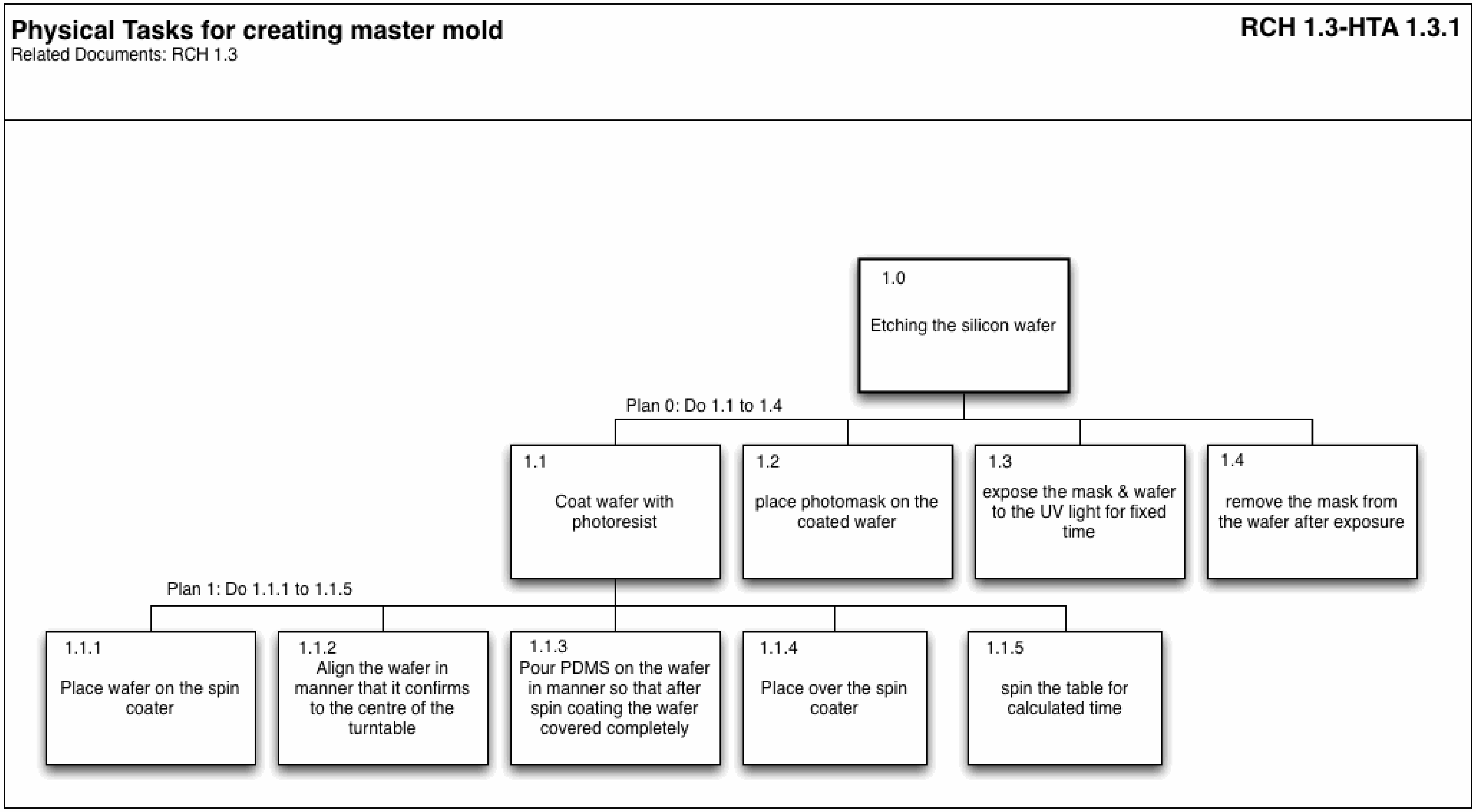


Figure 5.17: Physical Tasks related to creation of master mold

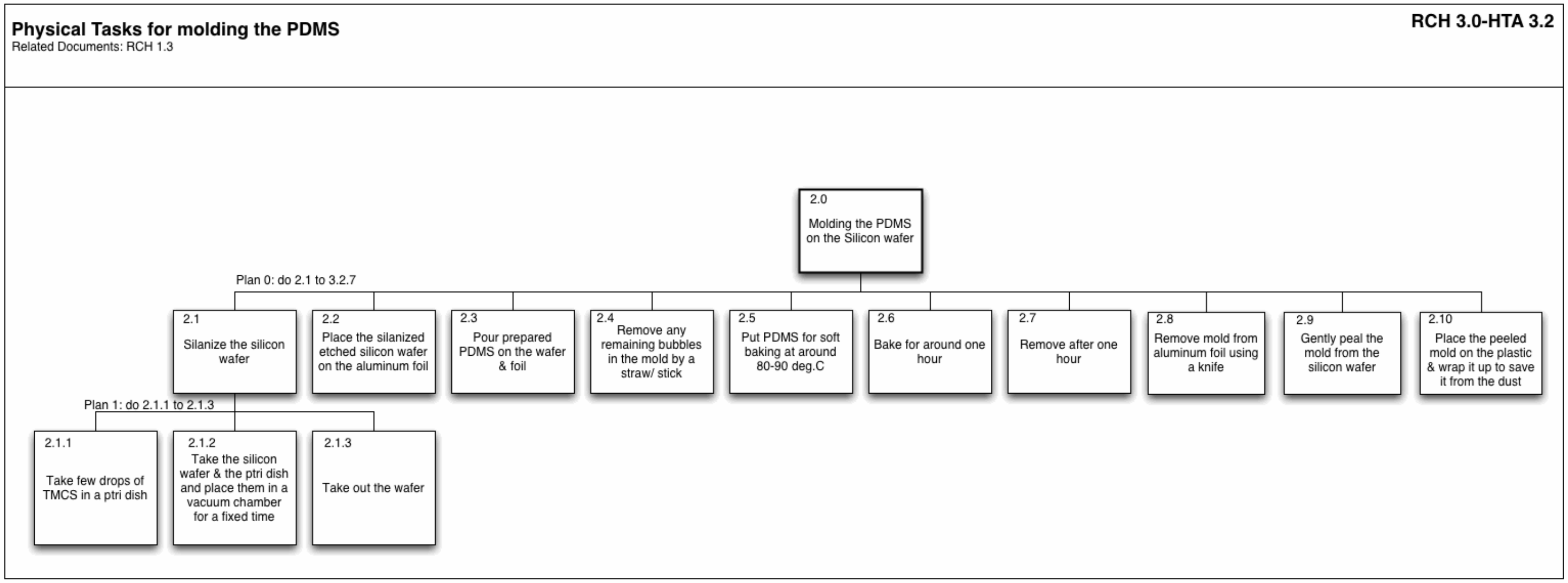


Figure 5.18: Physical tasks for molding the PDMS

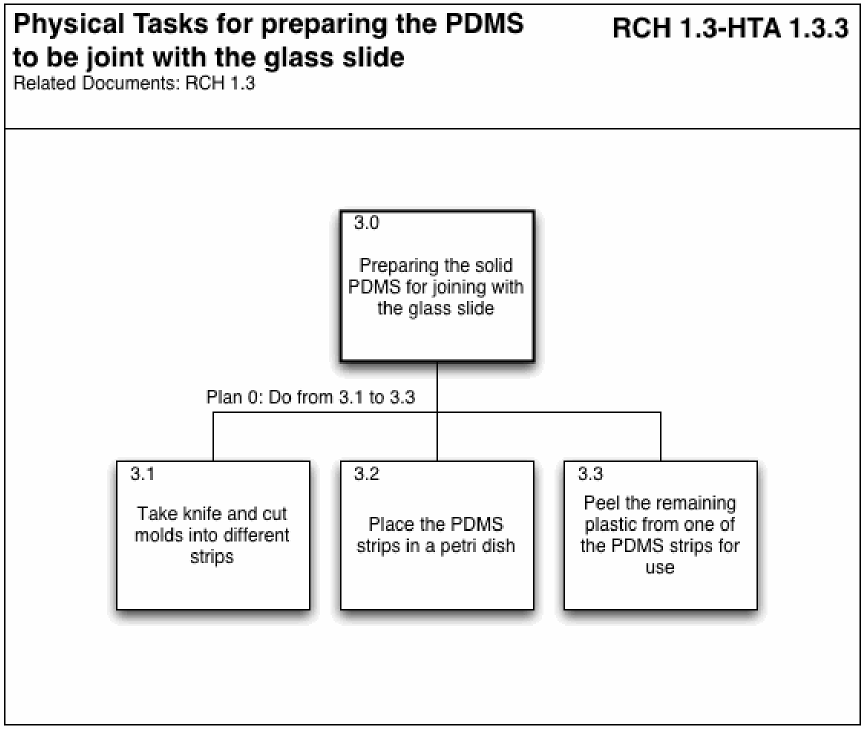


Figure 5.19: Physical tasks for preparing the PDMS to be joint with the glass slide

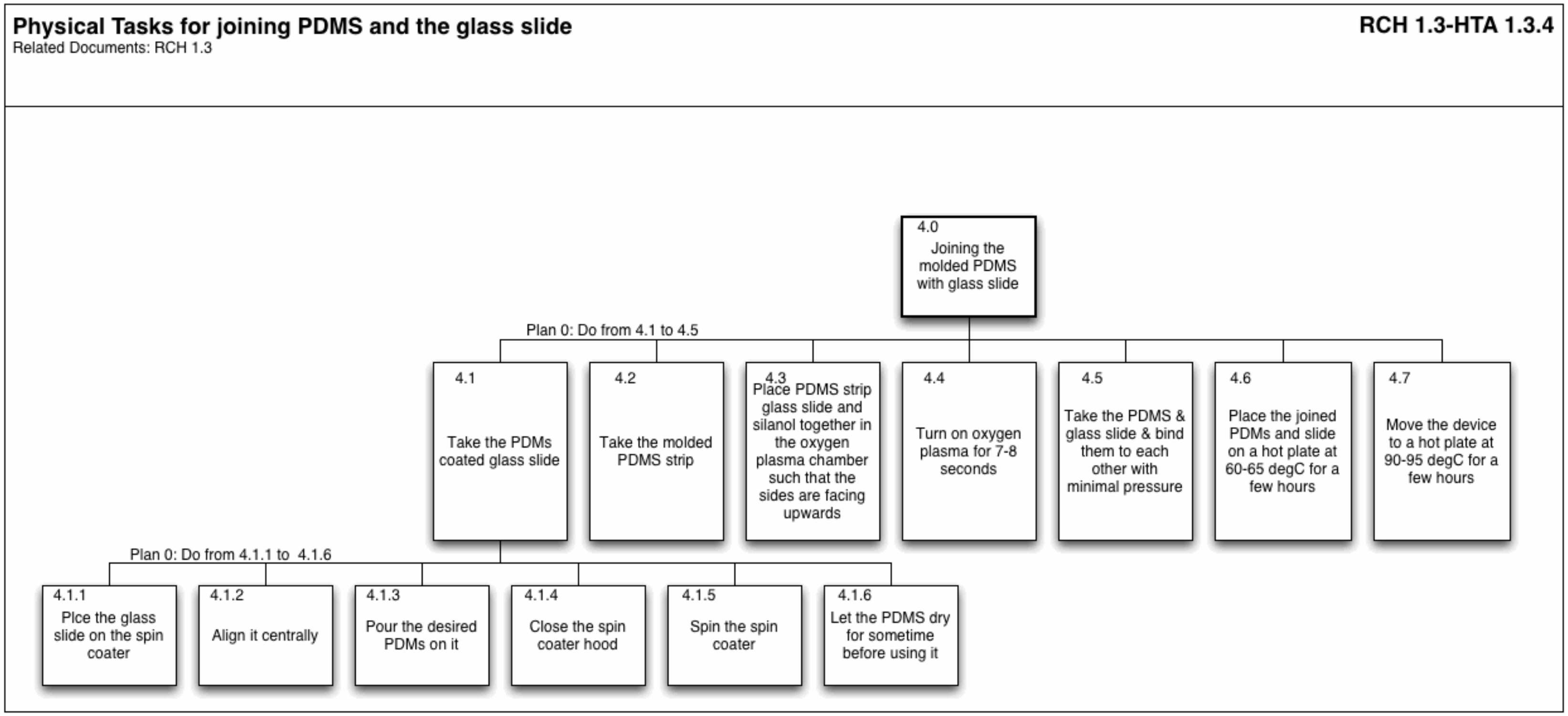


Figure 5.20: Physical tasks for joining the PDMS and glass slide

5.3.3 Comparison between CWA and WIDF for Phase 1

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
	RCH Environment (equivalent to AH in CWA)	Present	Present
1.	Functional Purpose	• Properly conceptualized chips • Correctly functioning chips	• Properly conceptualized chips • Correctly functioning chips
2.	Abstract Function	• Conservation laws of fluid dynamics • Conservation of mass for stoichiometric relations	• Conservation laws of fluid dynamics • Conservation of mass for stoichiometric relations
3.	Generalized Function	• Chemical Processes related to creation of master mold • Chemical and physical processes related to creating LOC device	• Chemical Processes related to creation of master mold • Chemical and physical processes related to creating LOC device
4.	Physical Function	• Spin Coater • Silicon Wafer • Photo Mask • Liquid PDMS • UV Light Exposure system • Photoresist Developer Chemical • PDMS coated Glass Slides • Silanizing Agent (TMCS) • Aluminum foil • Plastic Wrap • Solid PDMS • Oxygen Service	• Spin Coater • Silicon Wafer • Photo Mask • Liquid PDMS • UV Light Exposure system • Photoresist Developer Chemical • PDMS coated Glass Slides • Silanizing Agent (TMCS) • Aluminum foil • Plastic Wrap • Solid PDMS • Oxygen Service

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
		Vacuum pump + Plasma Cleaner	Vacuum pump + Plasma Cleaner
5.	Physical Form	• Spin speed repeatability: < 0.2 rpm; Spin speed resolution: < 0.2 rpm; Substrate sizes: < 1 cm to 200 mm round; 7 inch x 7 inch square; 71.1 cm W x 48.3 cm D x 45.7 cm H; Machine Weight: 165 lb (74.8 kg) • Circular (around 150 mm diameter) • 8 x 8 in; 1000 W exposure • Viscous Liquid • Liquid • Solid • 1/8" NPT 3-way valve; Weight: 13 lbs; Size: 8.5" H x 10" W x 8" D + pump speed: 1.4 m3/hr; total pressure: 200 mTorr	• Spin speed repeatability: < 0.2 rpm; Spin speed resolution: < 0.2 rpm; Substrate sizes: < 1 cm to 200 mm round; 7 inch x 7 inch square; 71.1 cm W x 48.3 cm D x 45.7 cm H; Machine Weight: 165 lb (74.8 kg) • Circular (around 150 mm diameter) • 8 x 8 in; 1000 W exposure • Viscous Liquid • Liquid • Solid • 1/8" NPT 3-way valve; Weight: 13 lbs; Size: 8.5" H x 10" W x 8" D + pump speed: 1.4 m3/hr; total pressure: 200 mTorr
6.	Use value (affordances)	• Settings of equipment that allow proper use for fabrication of chips • Properties that aid or hamper workability of materials • Properties of materials hazardous for health (e.g.TMCS)	
	RCH Agent	Present	Not present as a whole except for SRK
7.	Intentions/ Personal Value Structures	• Conceptualize chips based on research	

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
		agenda and specifications - Fabricate the devices correctly for them to work, according to the specifications	
8.	Abstract Information Processing / Psychological Laws/ Physical Laws	- Information Processing and decision making related to device fabrication	
9.	Psychological Mechanisms	- Decision making (based on materials & equipment) - Visual and haptic perception (for pouring the PDMS for proper spin coating) - Attention towards particular area of workspace (during spin coating for proper alignment) - Haptic perception for precision cuts of the molded PDMS	
10.	Physiological Function	- Perceptual-motor coordination for spin – coating - Perceptual-motor coordination for appropriate force applied for precision cuts - Perceptual motor coordination for proper stance and body posture for working with hazardous chemicals	
11.	Physical, Psychological	- Proper mindfulness to	

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
	Makeup/Anatomical form	apply concepts & assess situations while fabrication • Proper health for long hours of standing while fabricating chips	
	Capabilities (equivalent to SRK in CWA)		
12.	Skills	• Dexterity	• Dexterity
13.	Rules	• Rules and guidance procedures for safe work in the lab • Rules and heuristics evolved from experience that enable proper fabrication of chips	• Rules and guidance procedures for safe work in the lab • Rules and heuristics evolved from experience that enable proper fabrication of chips
14.	Knowledge	• Background knowledge of nanotechnology, fabrication and abstract theory	• Background knowledge of nanotechnology, fabrication and abstract theory
	RCH -Act	Present	Not present as a whole (except for Decision Ladder and Strategies Analysis)
15.	Functional Purpose	• Devise a chip which is properly conceptualized • Devise a chip which is properly fabricated	
16.	Abstract information processing/ Meaning Processing Activities (equivalent to Decision Ladder in CWA)	• Information processing for creating the chips	• Information processing for creating the chips
17.	Generalized Strategies (equivalent strategies analysis in CWA)	• Strategies for aligning slides centrally on the spin coater • Strategies for proper	• Strategies for aligning slides centrally on the spin coater • Strategies for proper

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
		spin coating • Strategies for cutting the PDMS • Strategies for joining (the molded PDMS & the Glass slide)	spin coating • Strategies for cutting the PDMS • Strategies for joining (the molded PDMS & the Glass slide)
18.	Physical Tasks	• Tasks related to creating the master mold • Tasks related to the coating of the Photoresist & PDMS. • Tasks related to the molding of the PDMS on Silicon Wafer. • Tasks related to the preparing the solid PDMS for joining with the glass base • Tasks related to the joining of the molded PDMS & the Glass slide • Avoiding Dust	
19.	Bodily/Physical changes (automatic)	• Automatic shift in attention due to task demands • Automatic adjustments during physical tasks	
20.	Interpreted Value	• Could be interpreted as conscious shifts; thus, provide ambiguity in partitioning the task flow for an external observer	

Table 5.13: Comparison between WIDF and CWA for Phase 1

5.4 Phase 2: Chip Testing

In phase 1, the chip was fabricated. In phase 2, the fabricated chip is tested. As described before, the chip testing occurs in a different section of the lab. Thus, in the system formulation, there was a division made between the two phases of fabrication and testing. In the rest of this chapter, phase 2, related to testing will be discussed in detail. Similar to the structure followed in phase 1, in this phase 2, the analysis related to CWA will be first presented followed by WIDF and a comparison between the two.

5.4.1 CWA

5.4.1.1 WDA

The first step in CWA is the work domain analysis. It involves constructing the abstraction hierarchy for testing the LOC device (AH 2.0, Figure 5.21). In AH 2.0, the functional purpose of this phase is the formulation for correctly functioning chips (according to specifications). At the next level of abstract function the conservation laws of fluid dynamics are prominent at this stage. As it was mentioned earlier in the discussion of phase 1 that the entity related to the laws of fluid dynamics was not developed in detail (see AH 1.0). In contrast, in phase 2, the laws of fluid dynamics are important, in the testing of the device, the main aim is to achieve a smooth laminar flow. Therefore, laws of fluid dynamics play a prominent role at the level of abstract function in testing of LOC devices in phase 2.

At the level of generalized function, the above laws are instantiated to first achieve a stable continuous flow. Once achieved, a proper laminar flow is important for conducting the experiments related to small-scale fluidics. The continuous flow and laminar flow are supported in the next level of physical function by the use of various devices having different capabilities. For example, at this level both hardware (pressure controller, microscope etc.) and software (LabVIEW/ microscope software) are used for achieving and maintaining continuous flow along with the laminar flow. Further, at this level of physical function, debris also plays an important role in the functioning of the device. Debris hinders the flow of the fluid through the device and therefore, the researcher actively tries to remove it. Thus, the absence of the debris allows for achieving a smooth laminar flow. Finally, at the level of physical form, the description of the physical attributes relevant to the functioning of the work domain is listed. These descriptions include the detailed specification of the microscopes as well as the nature of the fluids (for e.g., immiscibility) used for the flow through the device.

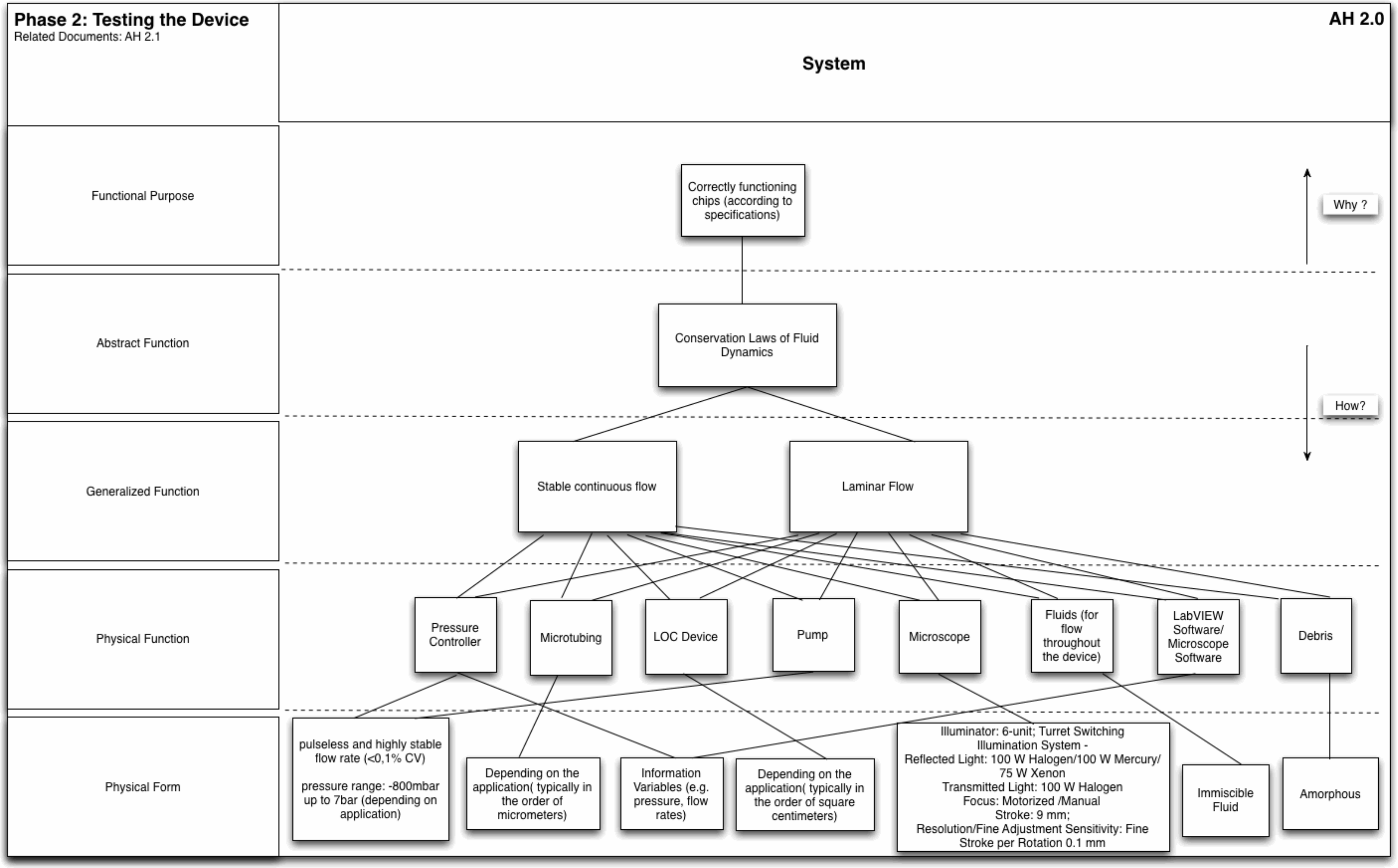


Figure 5.21: AH for testing the device in phase 2

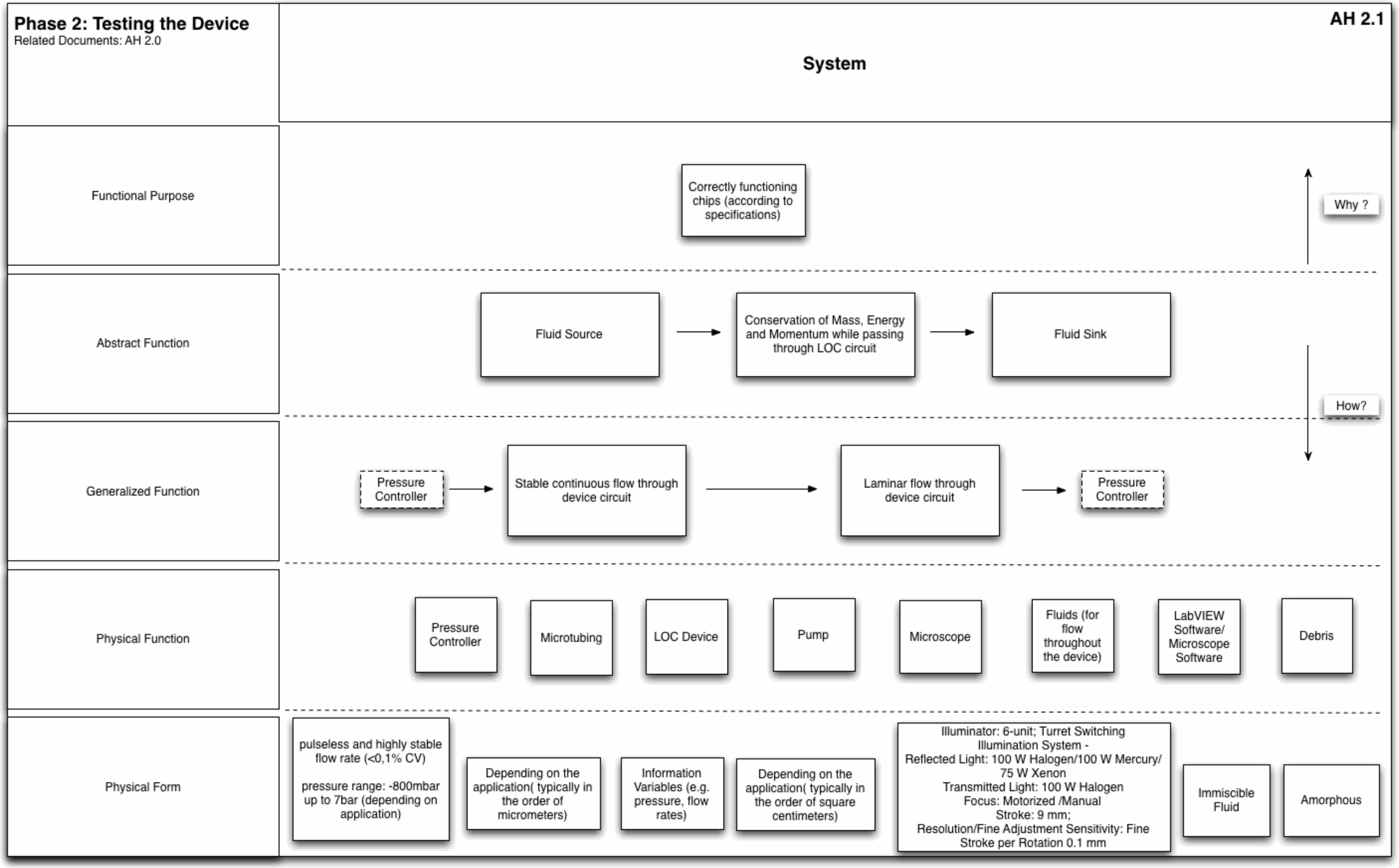


Figure 5.22: AH causal representation for Phase 2

WDA 2.0

Phase 2:Testing the Device Related Documents: AH 2.0	**System**	**Sub-System**	
		LOC Device	**Supporting Sub System**
Functional Purpose	Correctly functioning chips (according to specifications)		
Abstract Function		Conservation of Mass, Energy and Momentum while passing through LOC flow circuit	Fluid Source Fluid Sink
Generalized Function		Stable continuous flow through device circuit Laminar flow through device circuit	
Physical Function		LOC Device Debris	LabVIEW Software/ Microscope Software Fluids (for flow throughout the device) Microscope Pump Microtubing Pressure Controller
Physical Form		Size of the LOC device depends on application LOC device (typically in the order of square centimeters) Immiscible Fluid Amorphous (for Debris)	Details of the Microscope Illuminator: 6-unit; Turret Switching Illumination System - Reflected Light: 100 W Halogen/100 W Mercury/75 W Xenon Transmitted Light: 100 W Halogen Focus: Motorized /Manual Stroke: 9 mm; Resolution/Fine Adjustment Sensitivity: Fine Stroke per Rotation 0.1 mm Details of the Pressure controller pulseless and highly stable flow rate (<0,1% CV) pressure range: -800mbar up to 7bar (depending on application)

Figure 5.23: Abstraction decomposition space for phase 2 testing the LOC device

Along with the functional description of the work domain, a causal description of the work domain is provided in AH 2.1 (Figure 5.22). In this causal description, the level of abstract function and generalized function are developed in detail. For the levels of abstract function, the fluid from the fluid source circulates through the tubules of the LOC device. In this circulation, the laws of fluid dynamics are involved. There is a conservation of mass, energy and momentum in fluid flow through the LOC device. After the circulation through the device, the fluid enters the fluid sink. Along with the abstract function, the generalized function involves two main entities related to the fluid flow. First, there is a need for stable continuous flow through the device. Once a continuous and a stable flow is achieved, the fluid is circulated until the variables enter the range of the laminar fluid flow that will enable the researcher to record data.

The abstraction decomposition space (WDA 2.0, Figure 5.23) is developed in detail along with the above two representations. In terms of decomposition, two main divisions were made – system level and sub-system level. At the sub-system level, there was distinction made in terms of LOC device and supporting sub-systems. This distinction allows for presenting the various aspects of the work domain at various levels corresponding to the whole system and the sub-systems. Thus, it allows for situating the LOC device in systemic terms as well as the supporting subsystems that allow for conducting research activity.

5.4.1.2 ConTA

The second step of the CWA consists of the control task analysis. In phase 2, the prominent control task in phase 2 relates to the testing of the device (Figure 5.24), to ascertain it is functioning correctly. Therefore, beginning with the detection of debris, the tasks are required for its ultimate removal from the device. The steps outlined below describe the control task analysis related to the testing phase.

Control task analysis of testing phase-Decision Ladder **DL 2.0**

Related documents: AH 2.0

Number	Ladder Code	Notes	Type	Abstraction Level
1	Activation	Detection of debris in	Activity	Physical Form

		the channels of the LOC		
2	Alert	An alert state is formed about the presence of debris	Knowledge State	Physical Form, Physical Function
3	Observation	Information about debris is gathered by visual inspection	Information Processing Activity	Physical Form, Physical Function
4	Set of Observations	The visual inspection is consolidated to form an observational state	Knowledge State	Physical Function, Generalized Function
5	Identify	The current state of the system and its relation to debris are identified	Information Processing Activity	Physical Function, Generalized Function
6	System state	The system state is formulated based on the variables related to pressure through the channel, flow rates etc. Further, identification of location and state of debris are also taken into account	Knowledge State	Physical Form, Physical Function, Generalized Function, Abstract Function
7	Interpret	Based on the system state, the location of debris, its quantity and the relation to the LOC device is interpreted in the overall system state	Information Processing Activity	Functional Purpose, Abstract Function, Generalized Function
8	Ambiguity	The interpretations are grouped together to provide an insight into the ambiguity, i.e. involved in the situation	Knowledge State	Functional Purpose, Abstract Function, Generalized Function
9	Evaluate	The ambiguous state of the situation is evaluated in order to comprehend the courses of action available. For e.g. Whether the debris and location are compatible and can be removed by higher flow pressure or reversing the flow	Information Processing Activity	Functional Purpose, Abstract Function
10	Ultimate goal	Based on an evaluation of the debris an ultimate goal state is formed	Knowledge State	Functional Purpose

11	Interpret	The goals are interpreted in the overall view of the system	Information Processing Activity	Functional Purpose, Abstract Function, Generalized Function
12	Goal state	Once the choice has been made, (i.e., whether to increase the flow or reverse the flow direction) it is consolidated into a goal state formulated in the last step	Knowledge State	Generalized Function, Physical Function
13	Define Task	The tasks of removing the debris from various parts of the LOC are defined on the basis of the goal states	Information Processing Activity	Generalized Function, Physical Function, Physical Form
14	Task	The various tasks of removing debris are consolidated together to form a task state	Knowledge State	Generalized Function, Physical Function, Physical Form
15	Formulate procedures	Based on the goal, detailed planning of procedures for removing the debris is done, based on the context in which they appear.	Information Processing Activity	Physical Function, Physical Form
16	Procedure	A procedure state is fixed based on the procedures formulated before.	Knowledge State	Physical Function, Physical Form
17	Execute	The procedures that have been formulated before and are then executed to remove the debris	Activity	Physical Function, Physical Form

Table 5.14: Details of Control task analysis for testing phase

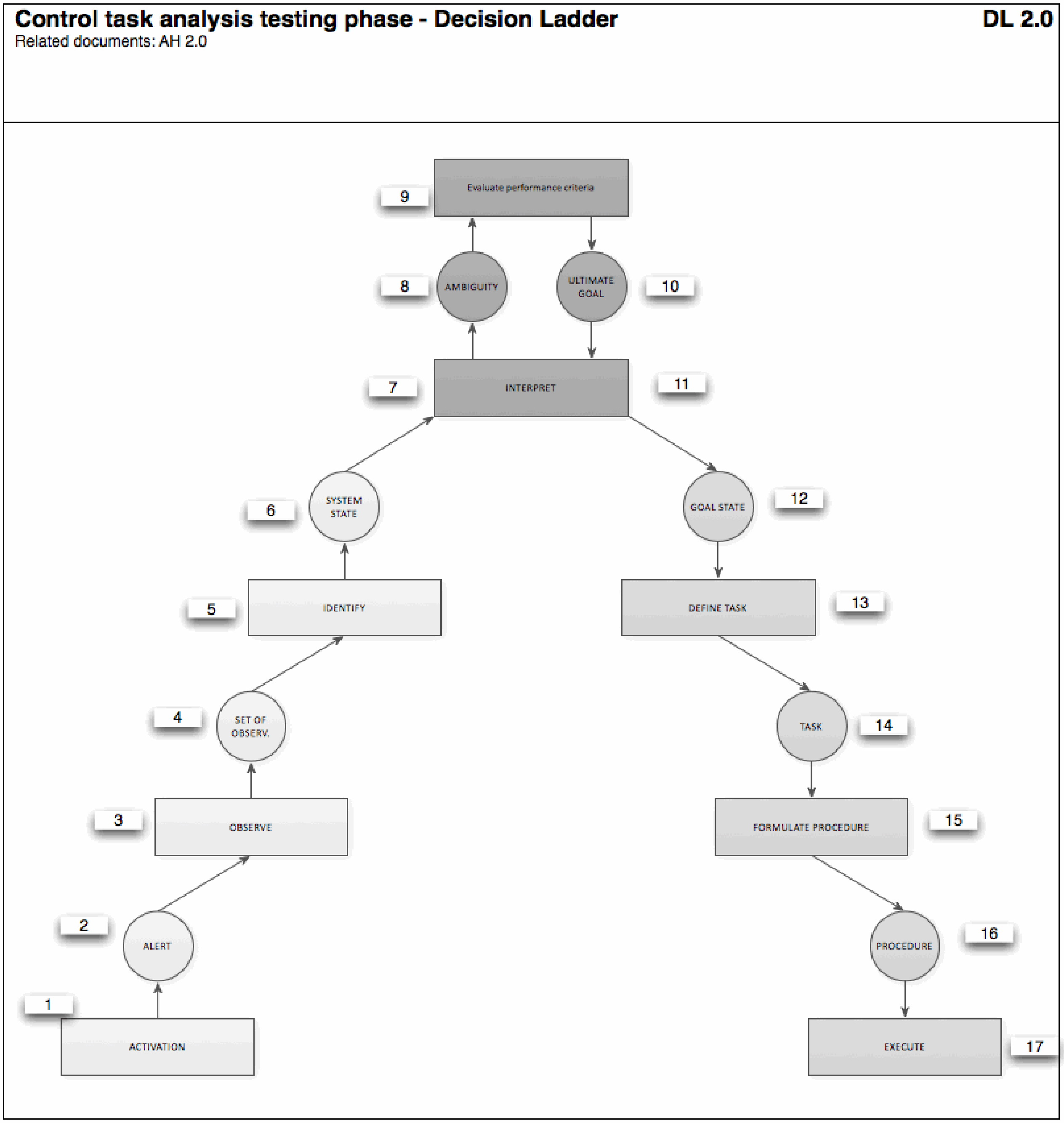


Figure 5.24: Control task analysis for testing the LOC device in phase 2

5.4.1.3 StrA

The third step of the CWA consists of the strategies analysis. In phase 2, there are two main strategies: strategies for getting rid of the debris (Figure 5.25) and strategies for minimizing turn around time during backflow (Figure 5.26).

Strategies for getting rid of the debris **StrA 2.1** Related documents: AH 2.0	
1	The first strategy for removing the debris consists of increasing the pressure flow. Once the flow pressure is increased, the increased fluid pressure acts on the debris and loosens it. In case the debris is not loosened, the pressure can be increased again to loosen it. However, the pressure flow cannot be increased indefinitely, as there is a chance of damage to the tubules of the device. The device can get damaged due to large amount of flow pressure. As a result, the limits of pressure can be imposed by heuristics based on experience or from theoretical calculations that identify the maximum permissible pressure.
2	A second strategy for removing debris is used when dealing with debris at some specific places, for e.g. L-shape joints. In cases involving L-shaped joints, if the debris is not removed then the flow through the device is reversed; i.e., the inlet tube is connected to the outflow exit and vice versa. This changing the direction of the flow allows for loosening the stuck debris in L-shaped tubule joints.

Table 5.15: Details of strategies for getting rid of the debris

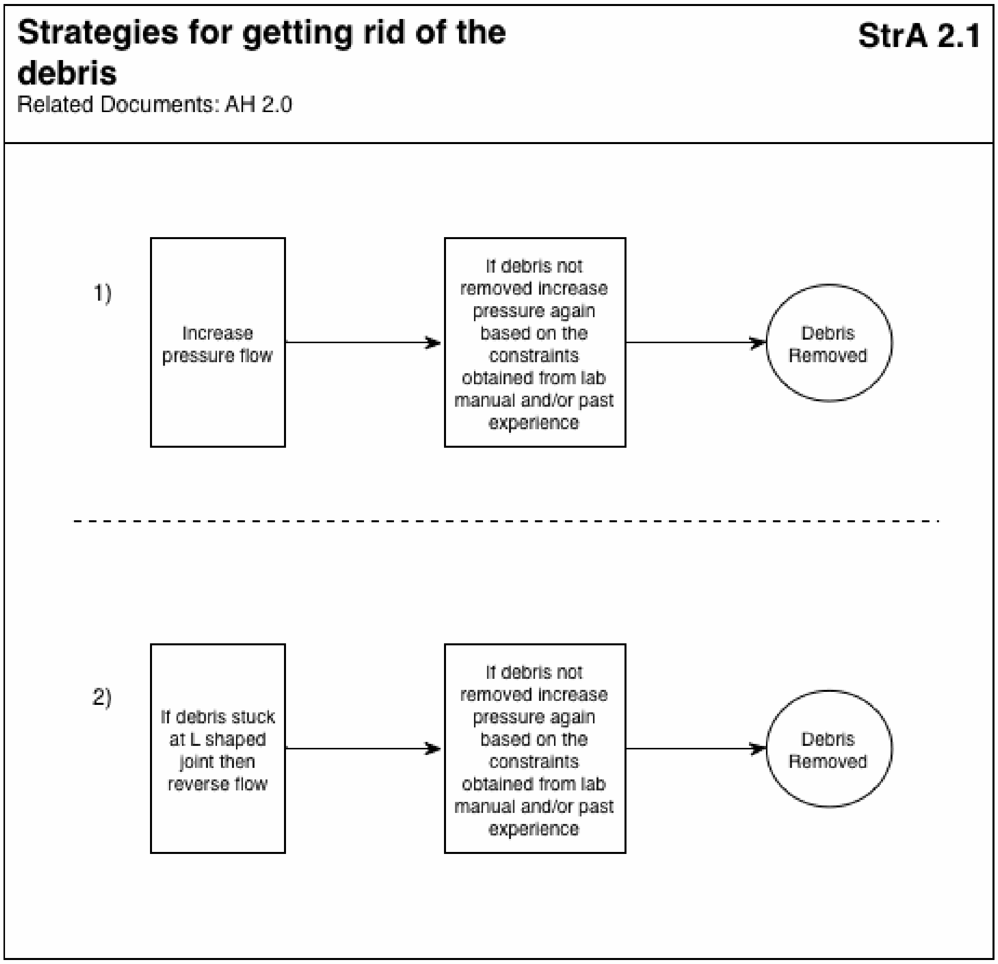


Figure 5.25: Strategies for getting rid of the debris

<table>
<tr><td colspan="2">Strategies for turn around time during backflow StrA 2.2
Related documents: AH 2.0</td></tr>
<tr><td>1</td><td>In the first strategy, to minimize backflow, the tube connecting the device and flow meter is selected such that it is long. Next this tube has to be periodically checked. If a drop of fluid 2 has entered this tube and has not gone beyond three-fourths the length of the tube, then the researcher continues the experiment. However, if the droplet passes three-fourths the length of the tube, the researcher unhooks the tube and lets the fluid drain until the droplet of fluid 2 exits the tube. Once the droplet exits, the tube is then reconnected and the fluid flow is stabilized. Disconnecting and reconnecting the tube leads to a loss of time. This is because it takes time for the fluid through the device to stabilize and be ready for data-collection procedures. Therefore, if the researcher is collecting data and the fluid 2 enters the flow circuit of fluid 1, having a longer tube enables the researcher some more time to continue data-collection before removal of the drop.</td></tr>
</table>

2	In order to successfully cut down on the data gathering time, researchers adopt another strategy. If the fluid 2 drop has entered the tube then decreasing the flow rate makes fluid 2 drop move slowly through the tube. Thus, if the researcher’s project requires readings to be taken at low flow rates, then the researcher continues with the data collection process. Thus, completing part of the data collection while the fluid 2 progresses slowly through the tube.

Table 5.16: Strategies for minimizing turn around time for backflow

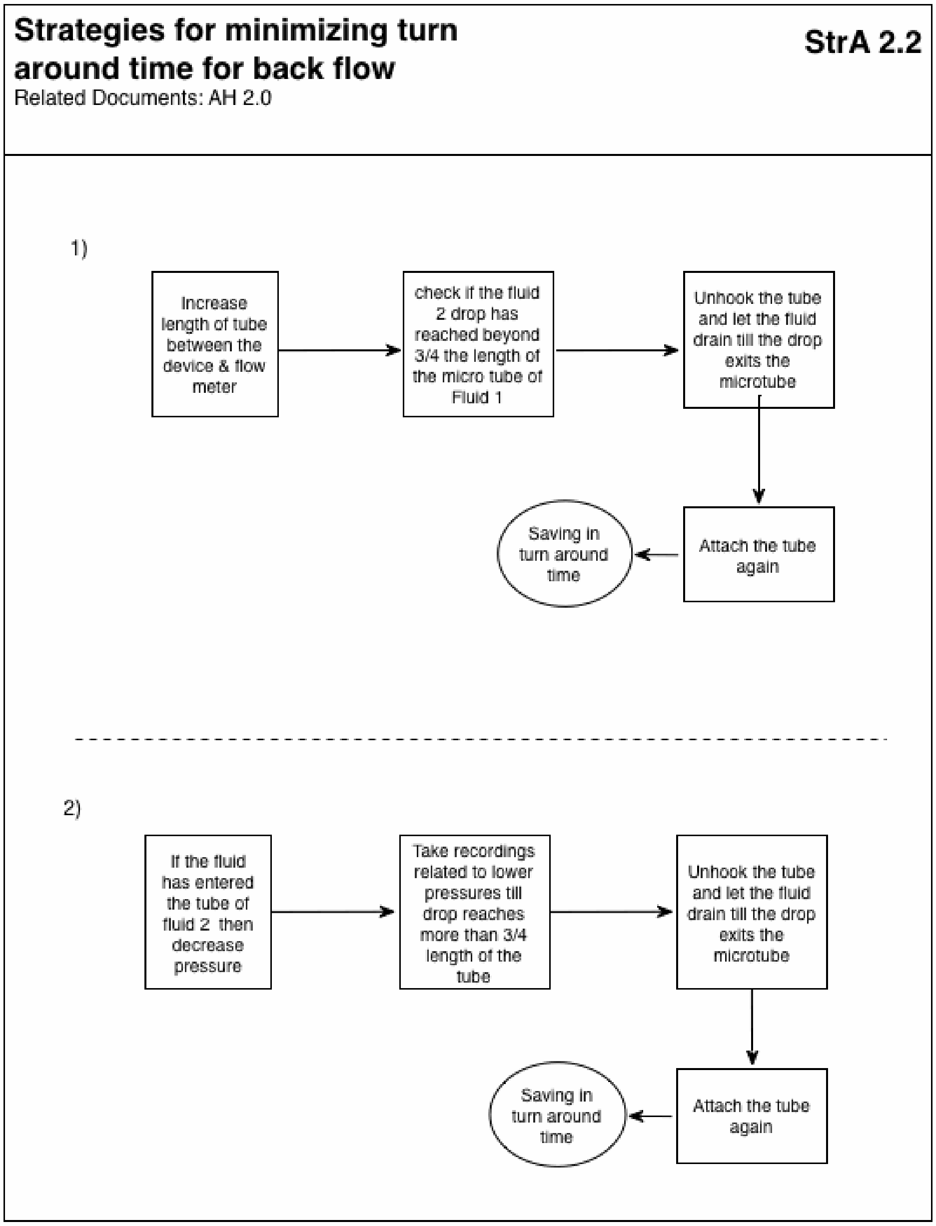


Figure 5.26: Strategies for minimizing turn around time for backflow

5.4.1.4 WCA

The last analysis for CWA for phase 2 is the worker competency analysis. In this analysis, the competencies required by the researchers are addressed. Thus, the following figure (SRK 2.0, Table 5.17) depicts the constraints related to the skills, rules and knowledge required for phase 2.

Worker competencies analysis				**SRK 2.0**
Related documents: AH 2.0, DL 2.0				
Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge- Based Behavior**
Associated Number	**Associated Number**			
Activation	Alert	Perceptual skills required for detecting the debris		
1	2			
Observation	Set of Observations	Perceptual skills required for gathering information about the location of debris throughout the LOC device	Rules for getting rid of the debris at various sites separately or in conjunction (i.e., two sites cleared at one time). Heuristics required for identifying potential areas that may be difficult to remove	Knowledge of sites of debris, as well as the reasoning required for the amount of maximum flow pressure that can be allowed
3	4			

Identify	System State	Perceptual skills required for identifying the system state, e.g. information variables from labVIEW software, flow of fluid across debris etc.	Heuristics related to the acceptable increase in the flow rate of the fluid.	Knowledge of the system state is formulated based on the knowledge of permissible flow pressures for which the device was conceived as well as knowledge based on theoretical calculation of the flow rates.
5	6			
Interpret	Ambiguity		Heuristics for identifying the state of the debris and possible cases of removal from the overall system	Reasoning skills required for identifying whether debris removal in particular cases is ambiguous or not
7	8			
Evaluate	Ultimate Goal			Reasoning skills to ascertain whether it is possible to attempt freeing debris or discarding the chip, based on the particular case. Further, knowledge of the overall deign of device is required for forming an ultimate goal based on the situation.
9	10			
Interpret	Goal State			Reasoning skills are required along with the knowledge of basic principles of fluidics. Knowledge is also required about the purpose of the device, to formulate a goal state to be reached for the removal of debris.
11	12			

Define Task	Task		Heuristics needed to decide whether to increase flow pressure under acceptable regimes or reverse the direction of flow. Also debris sites are addressed based on the priority and ease of fluid through the particular case.	Knowledge of fluid dynamics is required for the permissible flow regimes.
13	14			
Formulate Procedures	Procedure		Heuristics are needed to formulate procedures to remove debris locations based on priority and ease of removal	Knowledge required about the overall debris locations as well as the background of fluid dynamics to formulate detailed plan of debris removal based on the LOC flow circuitry
15	16			
Execute		Perceptual and motor skills to execute the steps for removing the debris		
17				

Table 5.17: Worker competency analysis for phase 2 for testing the chip

5.4.2 WIDF

5.4.2.1 RCH Environment

The first hierarchy in WIDF is the RC hierarchy corresponding to the environment. In the present case, the first layer of the RCH 2.1 (Figure 5.27) consists of correctly functioning chips (according to specifications). Next at the level of the abstract function, the conservation laws of fluid dynamics prevail. As highlighted earlier in the phase 1 (device fabrication), the conservation laws of fluid dynamics play a role in conceptualization of the device. However, their major role can be observed in phase 2, where the conservation of mass, energy and momentum of the fluid is important for testing of the device.

At the third level of the generalized function, there is a need for stable continuous flow and laminar flow. The stable continuous flow can be achieved by the equipment and associated software that is described at the level of physical function. At this level of physical function, there are various equipment such as pressure controller, LOC device, pump etc., as well as associated software, such as LabVIEW. Further, debris plays a major role in this level. Debris has an impact on the flow characteristics of the fluid and the researcher's aim is to free the device of the debris. The characteristics of the level of the physical form where the details of their appearance are provided. For example, in the level of physical form, the details of the pressure range and flow rate of the pressure controller are necessary for understanding the flow of the fluid. Along with these levels, the use value layer of the RCH also highlights the need for the correct range of the fluid flow that is permissible for the particular research project. Further, proper range of values are required for software to aid in data-collection for the research project. Finally, the fluids used for experiments could be hazardous (depending on the fluids used). Since this is not always the case, the line connecting the entity to the level above is shown as dashed.

Along with the functional representation of the work domain, the causal representation is also provided in RCH 2.1.1 (Figure 5.28). In this representation, two levels are described in detail—abstract function and generalized function. In the level of abstract function, the fluid begins from the fluid source. While moving through the LOC device there is a conservation of mass, energy and momentum. Finally, the fluid exits the device into the fluid sink. Next, at the level of generalized function, the fluid first achieves a stable continuous flow. This is possible by the removal of the debris from the flow circuit. Once the flow is continuous and stable, there is the need for achieving laminar flow for proceeding with the data collection.

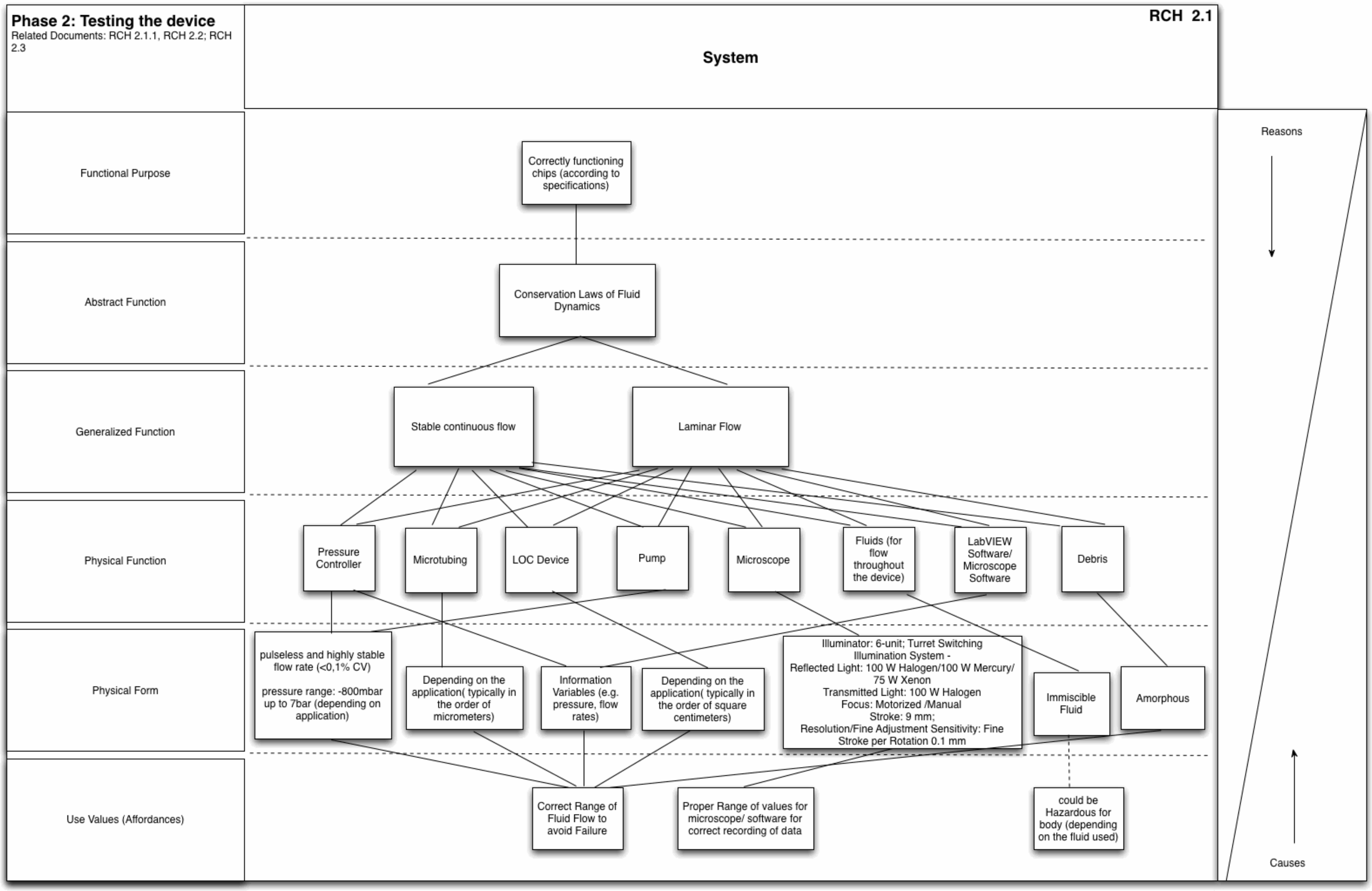


Figure 5.27: RCH Environment for Testing the Device

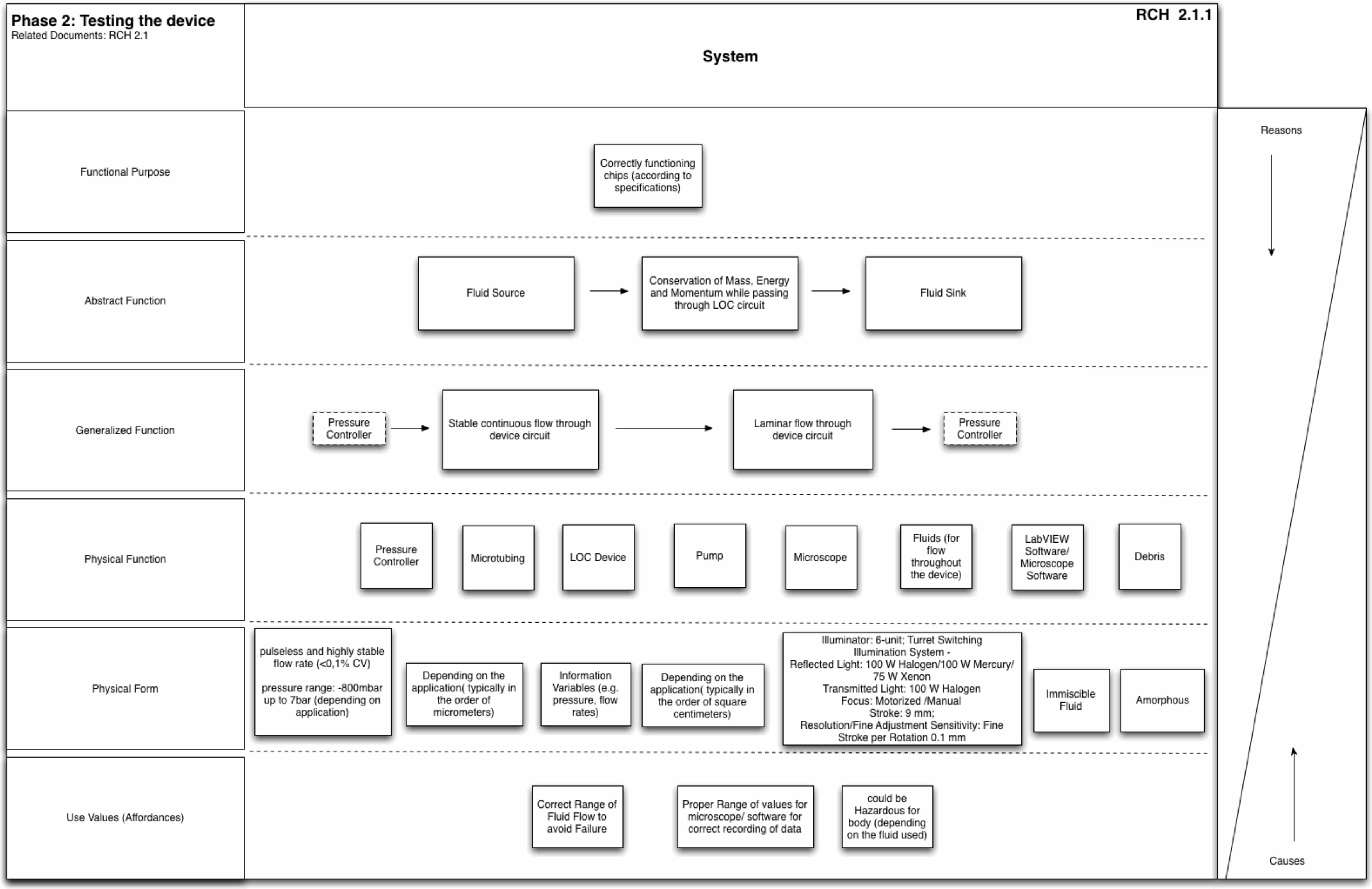
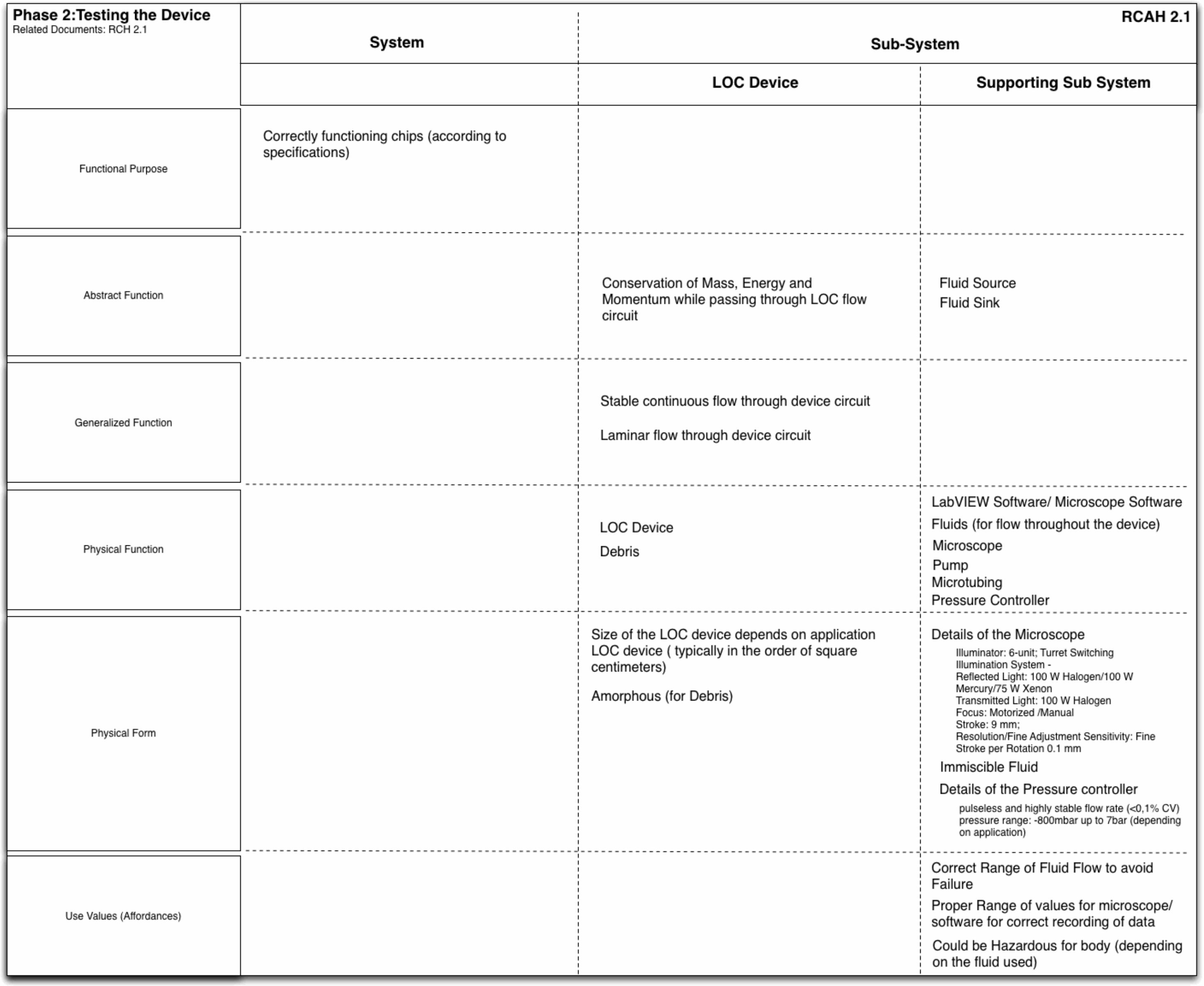


Figure 5.28: Causal representation of RCH environment for testing the device in phase 2



Phase 2:Testing the Device Related Documents: RCH 2.1	**System**	**Sub-System**	**RCAH 2.1**
		LOC Device	**Supporting Sub System**
Functional Purpose	Correctly functioning chips (according to specifications)		
Abstract Function		Conservation of Mass, Energy and Momentum while passing through LOC flow circuit	Fluid Source Fluid Sink
Generalized Function		Stable continuous flow through device circuit Laminar flow through device circuit	
Physical Function		LOC Device Debris	LabVIEW Software/ Microscope Software Fluids (for flow throughout the device) Microscope Pump Microtubing Pressure Controller
Physical Form		Size of the LOC device depends on application LOC device (typically in the order of square centimeters) Amorphous (for Debris)	Details of the Microscope Illuminator: 6-unit; Turret Switching Illumination System - Reflected Light: 100 W Halogen/100 W Mercury/75 W Xenon Transmitted Light: 100 W Halogen Focus: Motorized /Manual Stroke: 9 mm; Resolution/Fine Adjustment Sensitivity: Fine Stroke per Rotation 0.1 mm Immiscible Fluid Details of the Pressure controller pulseless and highly stable flow rate (<0,1% CV) pressure range: -800mbar up to 7bar (depending on application)
Use Values (Affordances)			Correct Range of Fluid Flow to avoid Failure Proper Range of values for microscope/ software for correct recording of data Could be Hazardous for body (depending on the fluid used)

Figure 5.29: Abstraction decomposition space for testing the device in phase 2

Along with the above two representations, an abstraction-decomposition space is used to understand the behavior of the parts and the whole system together (RCAH 2.1, Figure 5.29). In this RCAH 2.1, the overall testing system is divided into subsystems. At the subsystem level, there is the LOC device and the supporting subsystem. At the overall systemic level, the purpose of phase 2 is to ascertain that the chips are functioning according to specifications. However at the subsystem level, the various entities are divided based on whether they belong to the LOC device or the supporting subsystem.

5.4.2.2 RCH Agent

Next to RCH for environment, the RCH for people (RCH 2.2, Figure 5.30) involved is now addressed. In this hierarchy, at the first level, there is an intention for the testing of the chip to ascertain whether it is functioning correctly. At the second level, there is information processing and decision making related to the operating of the equipment, for testing the chips. At the third level, the abstract information processing and decision-making are instantiated in the form of visual attention required for assessing the chips as well as assessing the flow, in relation to the debris. These entities are instantiated in terms of the perceptual-motor coordination related to the assessing of situation for the flow as well as the perceptual motor coordination to ensure proper working of the flow circuit. Proper perceptual-motor coordination is possible due to the presence of proper mindfulness and endurance in the level related to “physical, psychological make-up/anatomical form”. Proper mindfulness is required to assess the problems in the LOC device; as well as to cope with the long hours required for testing. Finally, at the last level related to the capabilities, the skills required include perceptual skills for discrimination to enable the detection of debris, as well as, gauging the flow through the LOC circuit. Further, there are rules and heuristics required for limiting pressure to a particular flow range based on data sheets as well as past experience of the researcher. Finally, for phase 2, to proceed properly, there is a requirement for the researcher to possess background knowledge of nanotechnology, fabrication process and abstract theory. Further, there is also the need for knowledge to understand how equipment and instruments function. The SRK has been developed further in SRK 2.0 (Table 5.18).

Skills, Rules and Knowledge required for RCH Agent **SRK 2.0**

Related documents: RCH 2.2

Information Processing /Activity Step (Ladder Code)	Resultant state (Ladder Code)	Skill-Based Behavior	Rule- Based Behavior	Knowledge- Based Behavior
Associated Number	**Associated Number**			
Activation	Alert	Perceptual skills required for detecting the debris		
1	2			
Observation	Set of Observations	Perceptual skills required for gathering information about the location of debris throughout the LOC device	Rules for getting rid of the debris at various sites separately or in conjunction (i.e., two sites cleared at one time). Heuristics required for identifying potential areas that may be difficult to remove	Knowledge of sites of debris, as well as the reasoning required for the amount of maximum flow pressure that can be allowed
3	4			
Identify	System State	Perceptual skills required for identifying the system state, e.g. information variables from labVIEW software, flow of fluid	Heuristics related to the acceptable increase in the flow rate of the fluid.	Knowledge of the system state is formulated based on the knowledge of permissible flow pressures for which the device was conceived as well as knowledge based on theoretical calculation of the flow rates.

5	6	across debris etc.		
Interpret	Ambiguity		Heuristics for identifying the state of the debris and possible cases of removal from the overall system	Reasoning skills required for identifying whether debris removal in particular cases is ambiguous or not
7	8			
Evaluate	Ultimate Goal			Reasoning skills to ascertain whether it is possible to attempt freeing debris or discarding the chip, based on the particular case. Further, knowledge of the overall deign of device is required for forming an ultimate goal based on the situation.
9	10			
Interpret	Goal State			Reasoning skills are required along with the knowledge of basic principles of fluidics. Knowledge is also required about the purpose of the device, to formulate a goal state to be reached for the removal of debris.
11	12			

Define Task	Task		Heuristics needed to decide whether to increase flow pressure under acceptable regimes or reverse the direction of flow. Also debris sites are addressed based on the priority and ease of fluid through the particular case.	Knowledge of fluid dynamics is required for the permissible flow regimes.
13	14			
Formulate Procedures	Procedure		Heuristics are needed to formulate procedures to remove debris locations based on priority and ease of removal	Knowledge required about the overall debris locations as well as the background of fluid dynamics to formulate detailed plan of debris removal based on the LOC flow circuitry
15	16			
Execute		Perceptual and motor skills to execute the steps for removing the debris		
17				

Table 5.18: Skills, Rules and Knowledge required for testing the chips in phase 2

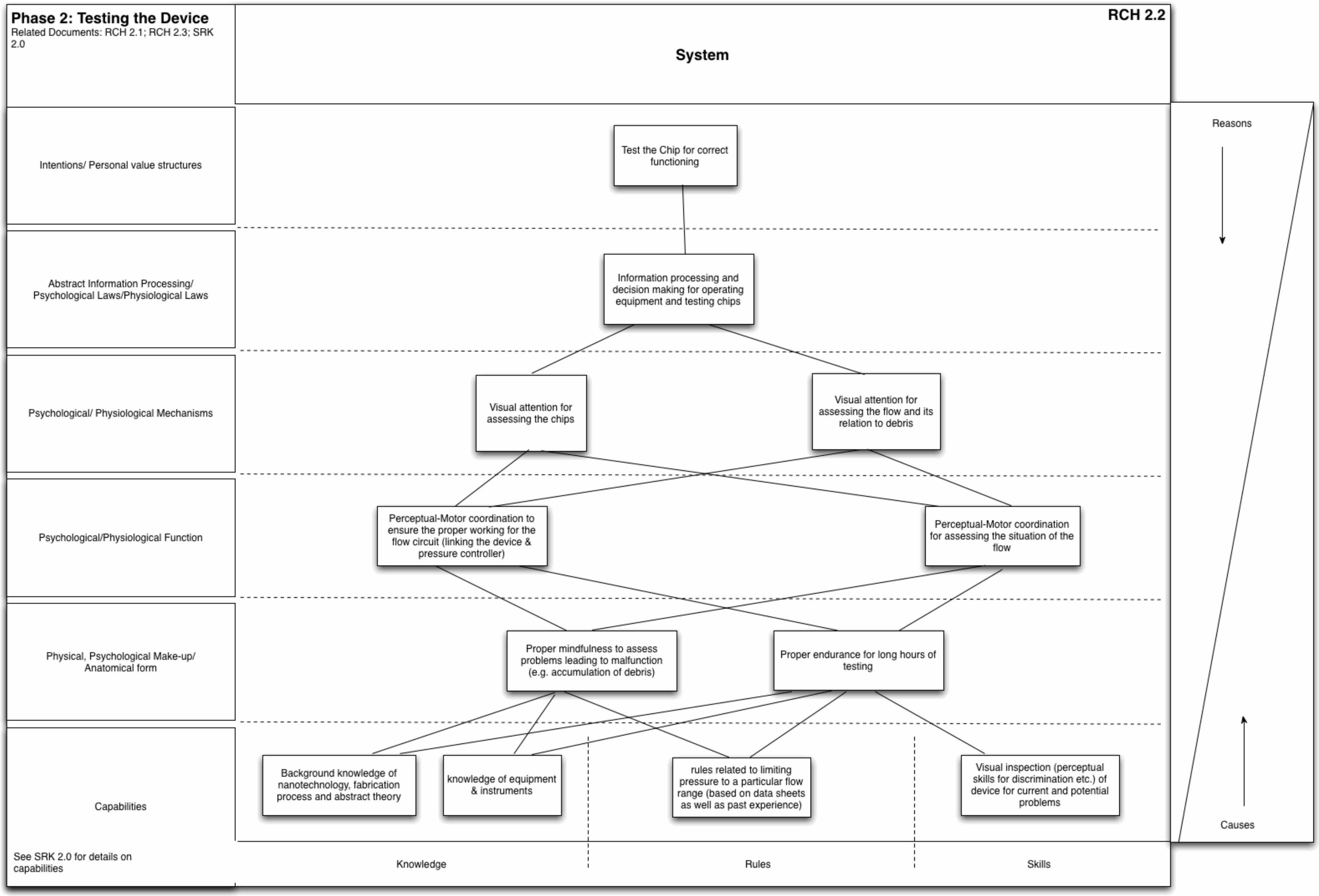


Figure 5.30: RCH Agent for testing the device in Phase 2

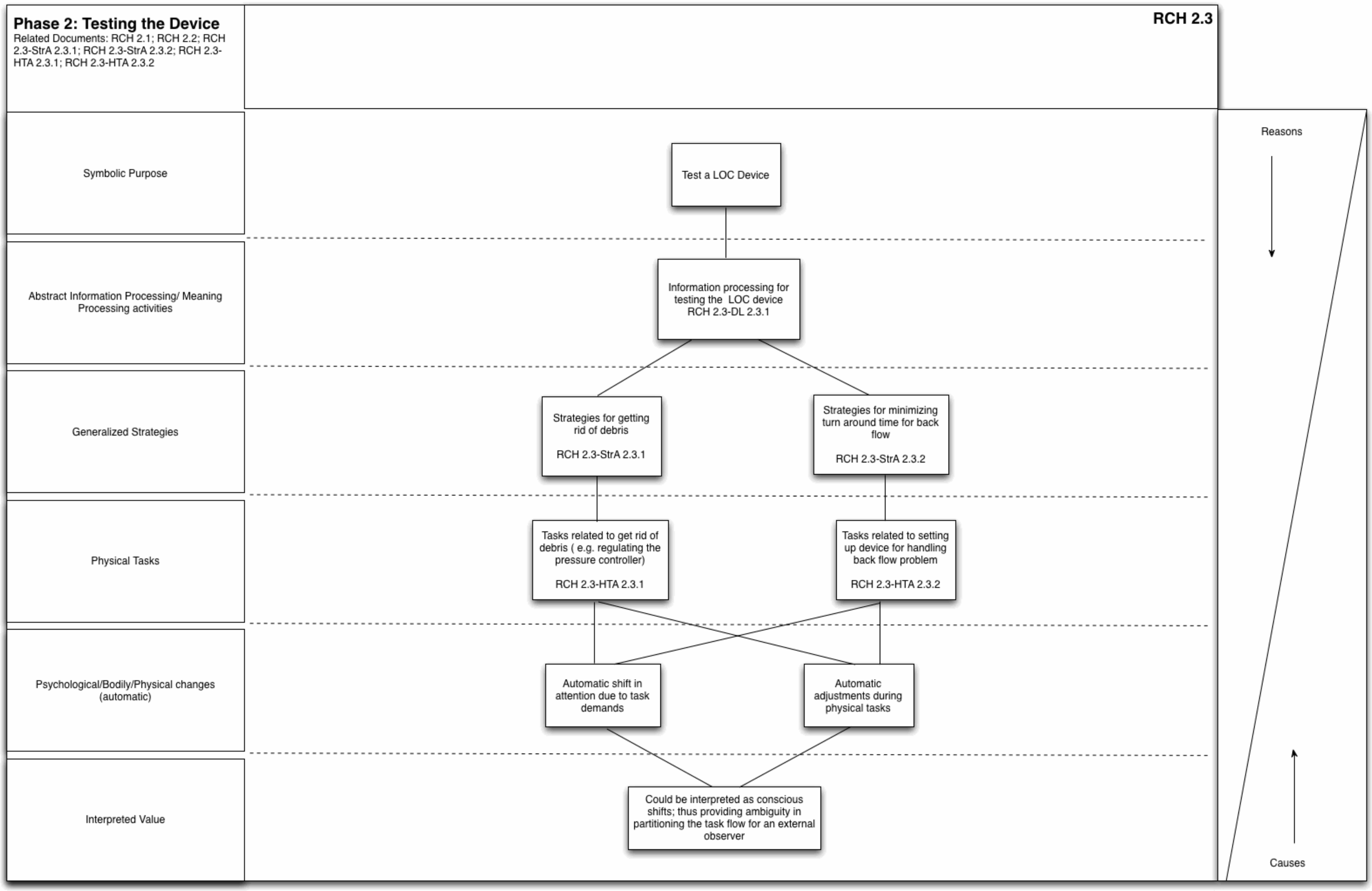


Figure 5.31: RCH Act for testing the device in phase 2

5.4.2.3 RCH Act

Along with the other two RC-Hierarchies, the third RC hierarchy pertains to Act (RCH 2.3, Figure 5.31). In this hierarchy, the first level of symbolic purpose involves testing a LOC device. At the second level, the purpose is instantiated in terms of the information processing for the testing the device. As described in chapter 4, the information processing activities can be developed using a decision ladder (RCH 2.3-DL 2.3.1, Figure 5.32; Table 5.19).

Information processing activities for testing phase **RCH 2.3-DL 2.3.1**

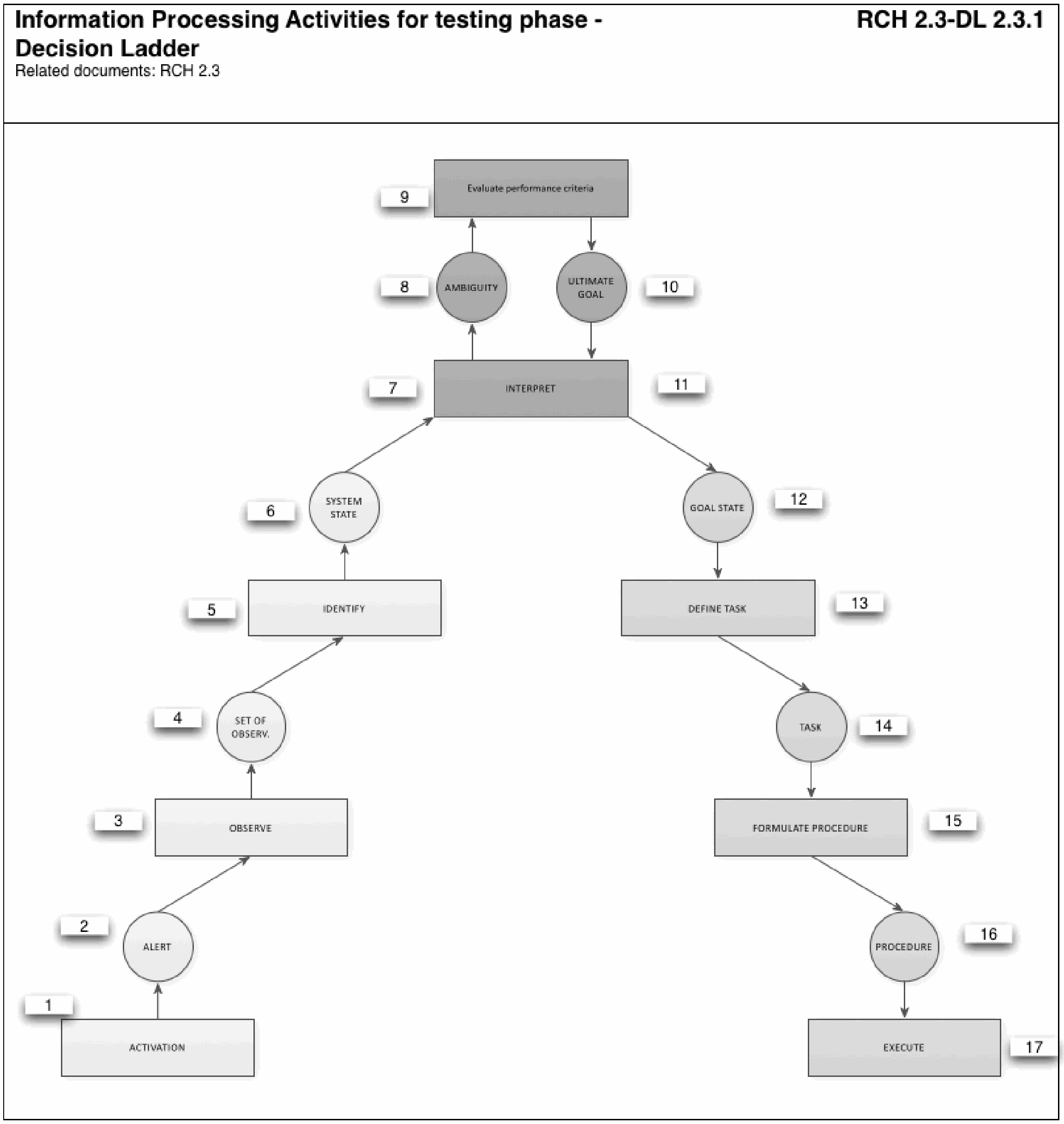
Related documents: RCH 2.3

Number	Ladder Code	Notes	Type	Abstraction Level
1	Activation	Detection of debris in the channels of the LOC	Activity	Physical Form
2	Alert	An alert state is formed about the presence of debris	Knowledge State	Physical Form, Physical Function
3	Observation	Information about debris is gathered by visual inspection	Information Processing Activity	Physical Form, Physical Function
4	Set of Observations	The visual inspection is consolidated to form an observational state	Knowledge State	Physical Function, Generalized Function
5	Identify	The current state of the system and its relation to debris are identified	Information Processing Activity	Physical Function, Generalized Function
6	System state	The system state is formulated based on the variables related to pressure through the channel, flow rates etc. Further, identification of location and state of debris are also taken into account	Knowledge State	Physical Form, Physical Function, Generalized Function, Abstract Function
7	Interpret	Based on the system state, the location of	Information Processing Activity	Functional Purpose, Abstract Function,

		debris, its quantity and the relation to the LOC device is interpreted in the overall system state		Generalized Function
8	Ambiguity	The interpretations are grouped together to provide an insight into the ambiguity, i.e. involved in the situation	Knowledge State	Functional Purpose, Abstract Function, Generalized Function
9	Evaluate	The ambiguous state of the situation is evaluated in order to comprehend the courses of action available. For e.g. Whether the debris and location are compatible and can be removed by higher flow pressure or reversing the flow	Information Processing Activity	Functional Purpose, Abstract Function
10	Ultimate goal	Based on an evaluation of the debris an ultimate goal state is formed	Knowledge State	Functional Purpose
11	Interpret	The goals are interpreted in the overall view of the system	Information Processing Activity	Functional Purpose, Abstract Function, Generalized Function
12	Goal state	Once the choice has been made, (i.e., whether to increase the flow or reverse the flow direction) it is consolidated into a goal state formulated in the last step	Knowledge State	Generalized Function, Physical Function
13	Define Task	The tasks of removing the debris from various parts of the LOC are defined on the basis of the goal states	Information Processing Activity	Generalized Function, Physical Function, Physical Form
14	Task	The various tasks of	Knowledge State	Generalized

		removing debris are consolidated together to form a task state		Function, Physical Function, Physical Form
15	Formulate procedures	Based on the goal, detailed planning of procedures for removing the debris is done, based on the context in which they appear.	Information Processing Activity	Physical Function, Physical Form
16	Procedure	A procedure state is fixed based on the procedures formulated before.	Knowledge State	Physical Function, Physical Form
17	Execute	The procedures that have been formulated before and are then executed to remove the debris	Activity	Physical Function, Physical Form

Table 5.19: Information processing tasks involved in testing the LOC devices in phase 2



Information Processing Activities for testing phase - Decision Ladder

Related documents: RCH 2.3

RCH 2.3-DL 2.3.1

Figure 5.32: Decision ladder for information processing activities for testing the chips in phase 2

Along with the decision ladder at the next level of generalized strategies, two main strategies appear. First, strategies for getting rid of the debris (Figure 5.33); second, strategies for minimizing turn around time for backflow (Figure 5.34). As described in chapter 4, this level of generalized strategies can be developed further in terms of information flow maps. These strategies are developed in detail below.

Strategies for getting rid of the debris	**RCH 2.3- StrA 2.3.1**
Related documents: RCH 2.3	
1	The first strategy for removing the debris consists of increasing the pressure flow. Once the flow pressure is increased, the increased fluid pressure acts on the debris and loosens it. In case the debris is not loosened, the pressure can be increased again to loosen it. However, the pressure flow cannot be increased indefinitely, as there is a chance of damage to the tubules of the device. The device can get damaged due to large amount of flow pressure. As a result, the limits of pressure can be imposed by heuristics based on experience or from theoretical calculations that identify the maximum permissible pressure.
2	A second strategy for removing debris is used when dealing with debris at some specific places, for e.g. L-shape joints. In cases involving L-shaped joints, if the debris is not removed then the flow through the device is reversed; i.e., the inlet tube is connected to the outflow exit and vice versa. This changing the direction of the flow allows for loosening the stuck debris in L-shaped tubule joints.

Table 5.20: Strategies for getting rid of the debris

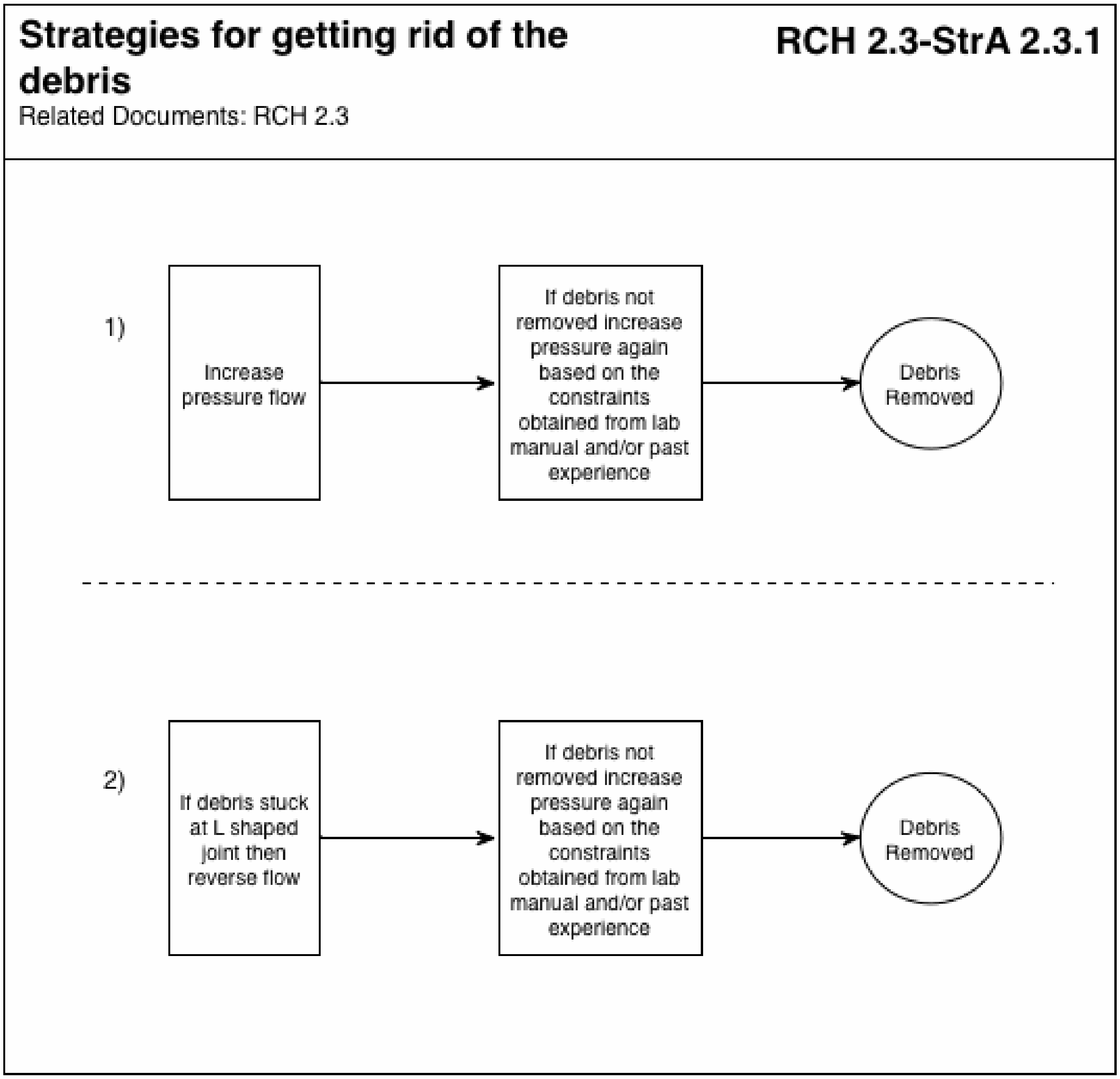


Figure 5.33: Strategies for getting rid of the debris during testing in phase 2

Strategies for minimizing turn around time during backflow **RCH 2.3- StrA 2.3.2** Related documents: RCH 2.3	
1	In the first strategy, to minimize backflow, the tube connecting the device and flow meter is selected such that it is long. Next this tube has to be periodically checked. If a drop of fluid 2 has entered this tube and has not gone beyond three-fourths the length of the tube, then the researcher continues the experiment. However, if the droplet passes three-fourths the length of the tube, the researcher unhooks the tube and lets the fluid drain until the droplet of fluid 2 exits the tube. Once the droplet exits, the tube is then reconnected and the fluid flow is stabilized. Disconnecting and reconnecting the tube leads to a loss of time. This is because it takes time for the fluid through the device to stabilize and be ready for data-collection procedures. Therefore, if the researcher is collecting data and the fluid 2 enters the flow circuit of fluid 1, having a longer tube enables the researcher some more time to continue data-collection before removal of the drop.
2	In order to successfully cut down on the data gathering time, researchers adopt another strategy. If the fluid 2 drop has entered the tube then decreasing the flow rate makes fluid 2 drop move slowly through the tube. Thus, if the researcher's project requires readings to be taken at low flow rates, then the researcher continues with the data collection process. Thus, completing part of the data collection while the fluid 2 progresses slowly through the tube.

Table 5.21: Details of the strategies for minimizing turn around time during backflow

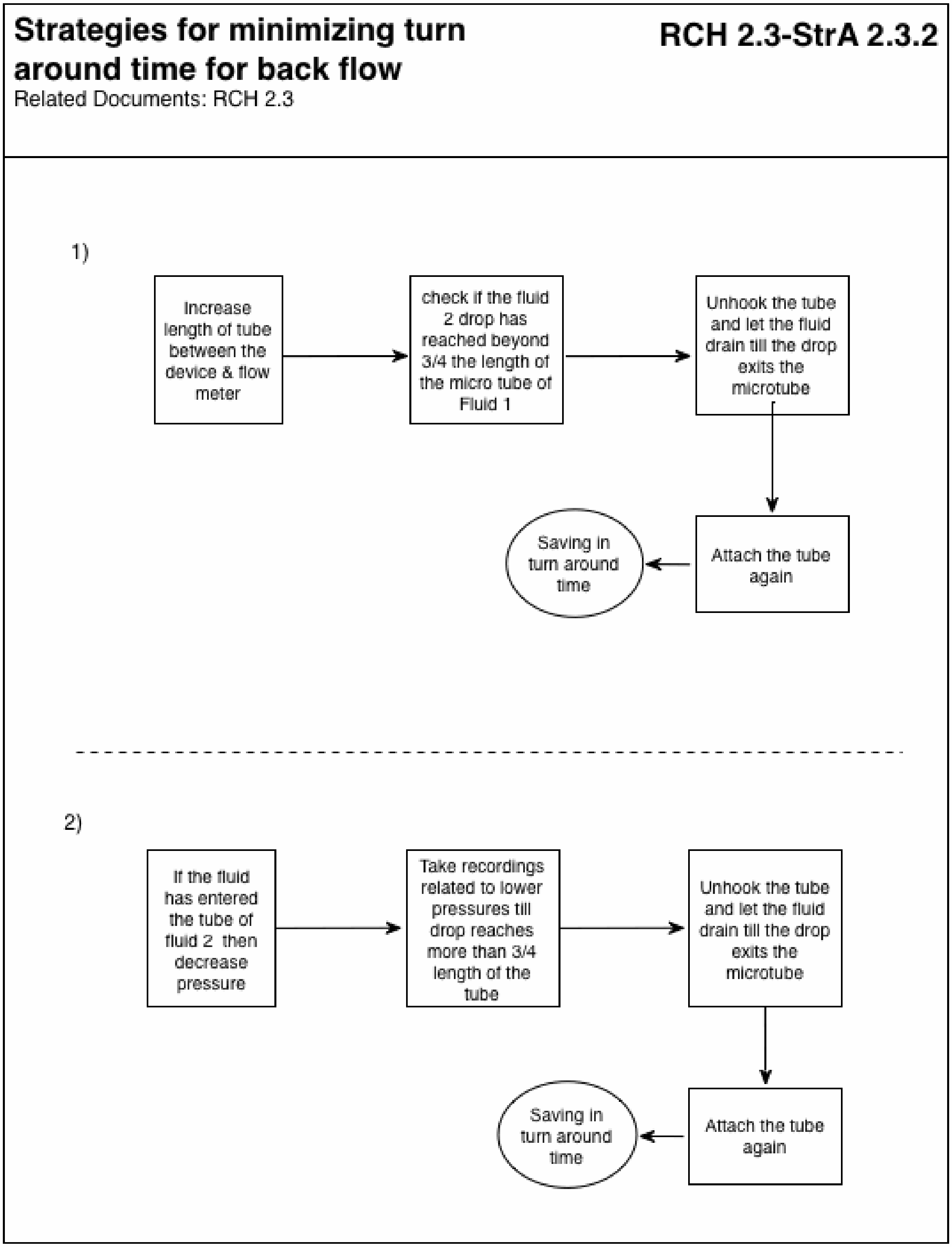


Figure 5.34: Strategies for minimizing turn around time for backflow during testing in phase 2

After the level of generalized strategies, the next level corresponds to physical tasks associated with the testing of the device. The first physical tasks involves regulating the pressure controller to get rid of the debris; while the second task involves setting up of the tubes and the pressure controller to handle the backflow problem. As described in chapter 4, these tasks can be developed further by use of the hierarchical task analysis (RCH 2.3-HTA 2.3.1, Figure 5.35; RCH 2.3-HTA 2.3.2, Figure 5.36).

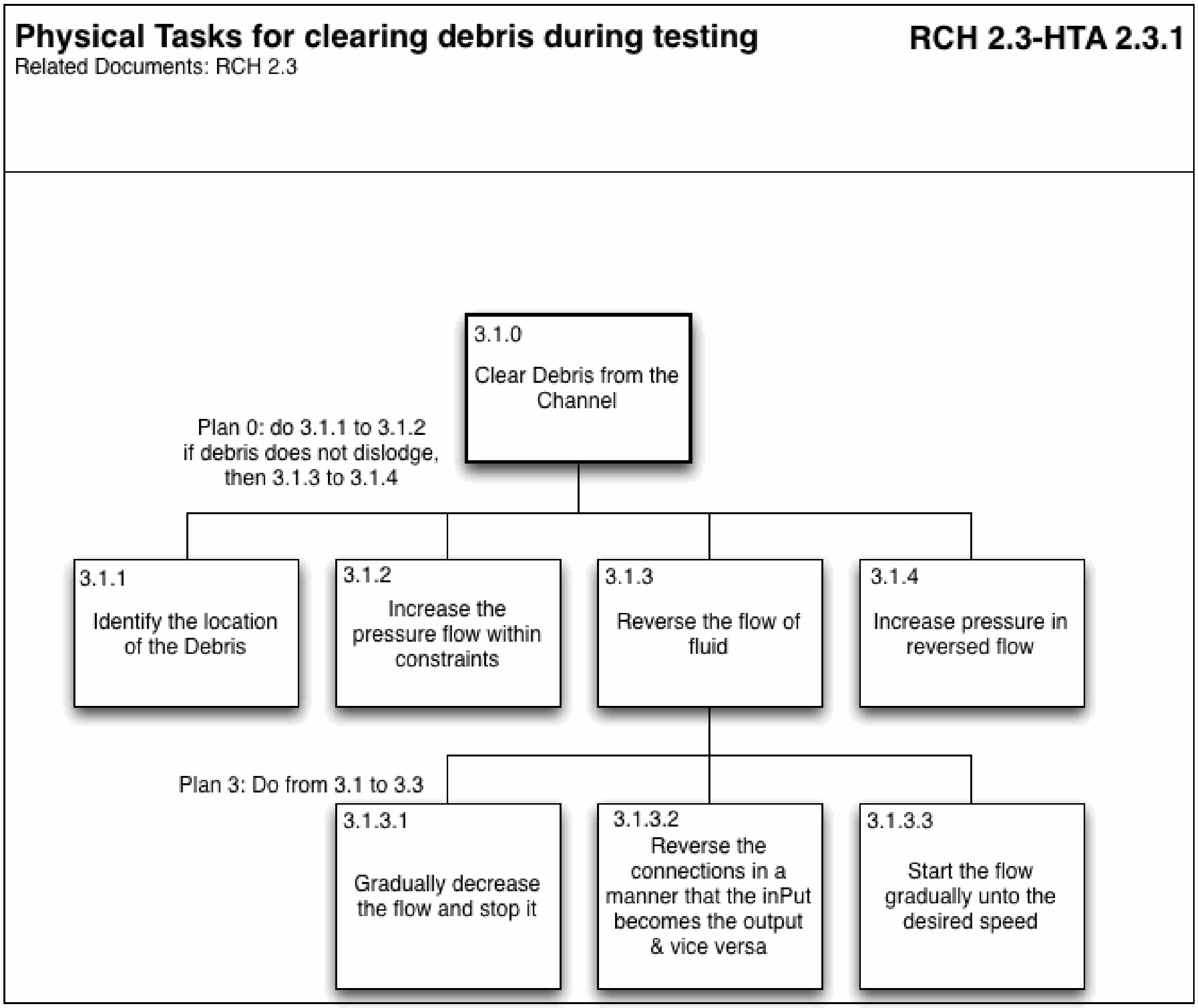


Figure 5.35: Physical tasks for clearing debris during testing

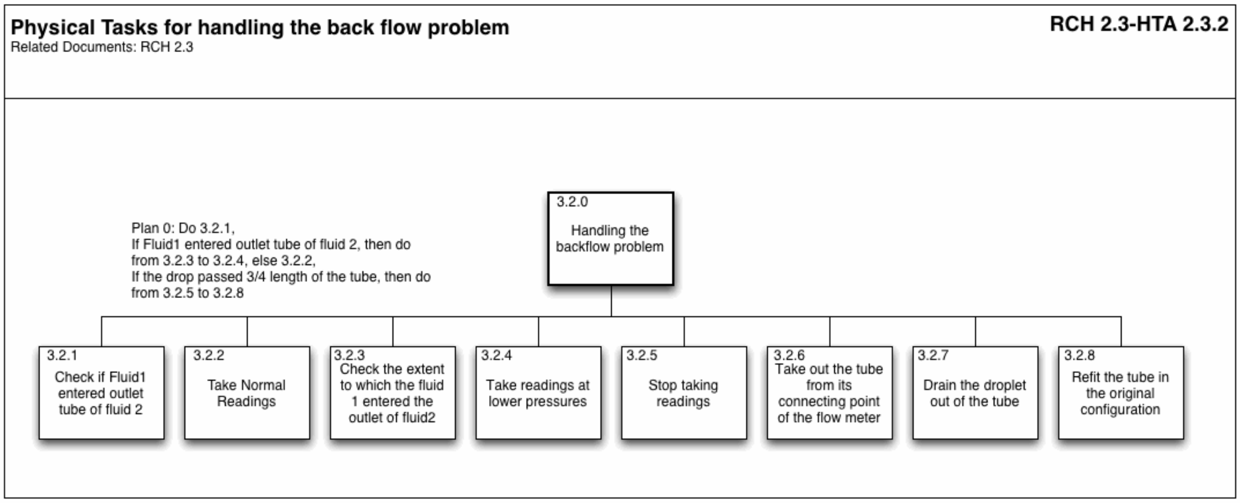


Figure 5.36: Physical tasks for handling the backflow problem

Along with the physical tasks, there are bodily changes that occur in the course of any activity. In the present case, at the fifth level, there are automatic shifts in attention due to task demands. Also, there are automatic adjustments during physical tasks. Finally, at the level of interpreted value, these automatic shifts could be interpreted as conscious shifts by other actors in the work domain. Thus hampering the optimal understanding or even the partitioning of the workflow. Such a situation is likely to happen when older members are training the younger members in the lab. After discussing the three RC hierarchies for WIDF, the requirements derived from using WIDF is compared to that of CWA (Table 5.22).

5.4.3 Comparison between WIDF and CWA for Phase 2

Comparison between WIDF and CWA for Phase 2

	Comparison Criteria	**WIDF**	**CWA**
	RCH Environment (equivalent to AH in CWA)	Present	Present
1.	Functional Purpose	• Correctly functioning chips (according to	• Correctly functioning chips (according to

Comparison between WIDF and CWA for Phase 2

	Comparison Criteria	**WIDF**	**CWA**
		specifications)	specifications)
2.	Abstract Function	- Conservation laws of fluid dynamics	- Conservation laws of fluid dynamics
3.	Generalized Function	- Stable continuous flow - Laminar flow	- Stable continuous flow - Laminar flow
4.	Physical Function	- Pressure Controller - Microtubing - LOC Device - Pump - Microscope - Fluids (for flow throughout the device) - LabVIEW software/ Microscope Software - Debris	- Pressure Controller - Microtubing - LOC Device - Pump - Microscope - Fluids (for flow throughout the device) - LabVIEW software/ Microscope Software - Debris
5.	Physical Form	- pulseless and highly stable flow rate (<0,1% CV); pressure range: -800mbar up to 7bar (depending on application) - Depending on the application (typically in the order of micrometers) - Information Variables (e.g. pressure, flow rates) - Depending on the application (typically in the order of square centimeters) - Illuminator: 6-unit; Turret Switching Illumination System - Reflected Light: 100 W Halogen/100 W Mercury/75 W Xenon; Transmitted Light: 100 W Halogen; Focus:	- pulseless and highly stable flow rate (<0,1% CV); pressure range: -800mbar up to 7bar (depending on application) - Depending on the application (typically in the order of micrometers) - Information Variables (e.g. pressure, flow rates) - Depending on the application (typically in the order of square centimeters) - Illuminator: 6-unit; Turret Switching Illumination System - Reflected Light: 100 W Halogen/100 W Mercury/75 W Xenon; Transmitted Light: 100 W Halogen; Focus:

Comparison between WIDF and CWA for Phase 2

	Comparison Criteria	WIDF	CWA
		Motorized /Manual; Stroke: 9 mm; Resolution/Fine Adjustment Sensitivity: Fine Stroke per Rotation 0.1 mm • Immiscible Fluid • Circular (around 150 mm diameter) • Amorphous	Motorized /Manual; Stroke: 9 mm; Resolution/Fine Adjustment Sensitivity: Fine Stroke per Rotation 0.1 mm • Immiscible Fluid • Circular (around 150 mm diameter) • Amorphous
6.	Use value (affordances)	• Correct Range of Fluid Flow to avoid Failure • Proper Range of values for microscope/ software for correct recording of data • Could be hazardous for body (depending on the fluid used)	
	RCH for Agent	Present	Not present as a whole except for SRK
7.	Intentions/ Personal Value Structures	• Test the Chip for correct	
8.	Abstract Information Processing / Psychological Laws/ Physical Laws	• Information processing and decision making for operating equipment and testing chips	
9.	Psychological Mechanisms	• Visual attention for assessing the chips • Visual attention for assessing the flow and its relation to debris	
10.	Physiological Function	• Perceptual-Motor coordination to ensure the proper working for the flow circuit (linking the device & pressure controller)	

Comparison between WIDF and CWA for Phase 2			
	Comparison Criteria	**WIDF**	**CWA**
		• Perceptual-Motor coordination for assessing the situation of the flow	
11.	Physical, Psychological Makeup/Anatomical form	• Proper mindfulness to assess problems leading to malfunction (e.g. accumulation of debris) • Proper endurance for long hours of testing	
	Capabilities (equivalent to SRK in CWA)		
12.	Skills	• Visual inspection (perceptual skills for discrimination etc.) of device for current and potential problems	• Visual inspection (perceptual skills for discrimination etc.) of device for current and potential problems
13.	Rules	• Rules related to limiting pressure to a particular flow range (based on data sheets as well as past experience)	• Rules related to limiting pressure to a particular flow range (based on data sheets as well as past experience)
14.	Knowledge	• Background knowledge of nanotechnology, fabrication process and abstract theory • Knowledge of equipment & instruments	• Background knowledge of nanotechnology, fabrication process and abstract theory • Knowledge of equipment & instruments
	RCH -Act	Present	Not present as a whole (except for Decision Ladder and Strategies Analysis)
15.	Symbolic Purpose	• Test a LOC Device	

Comparison between WIDF and CWA for Phase 2

	Comparison Criteria	**WIDF**	**CWA**
16.	Abstract information processing/ Meaning Processing Activities (equivalent to Decision Ladder in CWA)	• Information processing for testing the LOC device	• Information processing for testing the LOC device
17.	Generalized Strategies (equivalent strategies analysis in CWA)	• Strategies for getting rid of the debris • Strategies for minimizing turn around time for backflow	• Strategies for getting rid of the debris • Strategies for minimizing turn around time for backflow
18.	Physical Tasks	• Tasks related to getting rid of the debris (e.g. regulating the pressure controller) • Tasks related to setting up the device for handling the backflow problem	
19.	Bodily/Physical changes (automatic)	• Automatic shift in attention due to task demands • Automatic adjustments during physical tasks	
20.	Interpreted Value	• Could be interpreted as conscious shifts; thus, providing ambiguity in partitioning the task flow for an external observer	

Table 5.22: Comparison between CWA and WIDF for phase 2

5.5 Conclusion

In chapter 4, the ethnography corresponding to the first step of the WIDF was presented. In this chapter 5, the second step of WIDF corresponding to the engineering analysis was conducted. Due to the nature of the domain under consideration, the system formulation identified two phases. Phase 1 consisted of fabrication of the LOC device, whereas Phase 2 consisted of testing the device. To demonstrate the requirements gathering capacity of WIDF, it was compared to CWA for both phases. The results show that due to the structure of the hierarchies of WIDF, it allows for more requirements to be gleaned from the domain under consideration. In the next two chapters (7 and 8) a different instance of nanotechnology, pertaining to the field of nanotechnology, is discussed in detail.

Chapter 6: Site 2—Robotics (Ethnographic Study)

6.1.1 Introduction

The ethnographic study presented in this chapter serves as the first step of the extended CWA for Site 2. In Site 1 (chapter 4), the primary focus was on devices. This study of Site 2 extends on the notions of devices, but considers a special class of devices — robots. Robots are entities, often depicted as displaying machine intelligence; i.e., they are depicted as "active" devices often straddling the boundaries between a human and a machine. The depiction of the robot as a mechanical creature has captured popular imagination from time immemorial (see Nocks, 2008 for a historical treatment). At times benign and at other times hostile, robots are a staple fare in the books and movies of the science fiction genre. Typically, robots are depicted as electromechanical devices with onboard power and often controlled by computer chips. However, one needs to pause and ask the question, when the robot is such that is barely visible to the naked eye, how can it have onboard power and also how can it be controlled?

To understand the challenges associated with robotics at the small scale, the present study addresses small-scale robots built by an undergraduate team, University of Waterloo Nano Robotics Group (UWNRG)[20]. UWNRG has won microrobotics challenges in the past (IEEE ICRA[21] robot challenges) and serves as a University of Waterloo pioneer undergraduate group in design, development and research in nanorobotics. This autonomous group is entirely composed of undergraduate students who arrange for funding, research, design and develop robots; as well as take part and at many times win international robotic competitions. This group serves as a good site for understanding the dimensions of robotics, as the robots they design for the competition have twin challenges of navigation and microassembly. These two challenges are an important part of more generic problems that are present in the field of nanorobotics. In developing robots for a design competition UWNRG uses two modes of robotic control. The first mode of control is autonomous, whereas in the second mode, the human is actively controlling the robot. In terms of HFE research, the second mode of control has implications for design of

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[20] http://www.uwnrg.org

[21] Institute of Electrical and Electronics Engineers (IEEE) International Conference on Robotics and Automation (ICRA)

interfaces for human robot interaction in micro/nanorobotics. The choice of UWNRG as a research group also presents a contrast to the other two sites. At UWNRG all the members were undergraduates, as compared to the other two sites where the participants were graduate students.

Further, UWNRG functioning demonstrates that they not only build robots, but also robotic ecologies; i.e., they gain funding, develop new robots and figure out potential lines of future activities. Thus, the robot that they build cannot be simply described as a technical challenge, but is best conceptualized as a sociotechnical challenge. The workings of this site also demonstrate the intricate connections between cost, design and development as a social process. Thus, the insights presented by this site are similar to those highlighted by the ethnographer-engineer Bucciarelli (1994). Bucciarelli (1994, p. 62) introduces the concept of “object worlds” to show how engineering design is a fundamentally social process. In object worlds, different people working within their different object worlds are constrained by the overarching requirements of these worlds. The participants have their shared concepts and shared vocabulary that provides intelligibility and understanding for technical design. Similarly, in this Site 2, UWNRG works in a world of robotics where the participants have a shared vocabulary built around the robot. However, even though “object world” is a good characterization, as this chapter will show, it does not completely address the aspects of motivation and self-organization capabilities of design and related patronage of UWNRG. Thus, I will use the term “robotic ecologies” to identify the activities that UWNRG is involved with while building robots, acquiring funding and managing themselves as a group.

6.1.2 Micro/Nanorobotics

Micro/Nanorobots are active structures that show the behavior of machine-intelligence, such as sensing and acting, and swarm behavior, among others. The idea of nanorobotics has been present for quite some time. However, the term “nanorobot” started gaining currency in the late 1990s and grew heavily in the 2000s (Mavroidis & Ferreira, 2013). The nanorobotics researchers Mavroidis and Ferreira (2013, p. 4) note that science fiction had an impact on the public imagination and has helped for the growth of the discipline. Currently, nanorobotics systems are divided into four major types: NanoManipulator systems; Bio-Based NanoRobotics Systems;

Magnetically guided NanoRobotics Systems; and BioMemetic Robotic Systems (Mavroidis & Ferreira, 2013; also see Weir, Sierra, Jones, 2005).

NanoManipulators are systems which make changes at the scale of micro/nanometers. The electronics industry often requires precise control and manipulation at the micro/nano level for devising Micro/Nano Electromechanical systems (MEMS/NEMS). Nanomanipulators require the human activity and present opportunities for interface design and teleoperation (for e.g. see Jalili, 2013, for an overview). Many nanomanipulators are present commercially. For example, DCG Systems (DCG, 2014) provides products for nanoprobing. Their platform, nProber II, provides capabilities for manipulating transistors on the scale of sub-14nm. This system also contains control software that brings all the components of the nanomanipulator together for successful operation. This software allows for improving operator productivity by providing visual feedback as well as guiding the user through each probing routine.

Along with manipulators, Nanorobotics is also developed in the area of BioNanorobotics (for e.g., see Lenaghan et al., 2013 for applications in cancer therapy). In this area, bio components such as DNA and proteins are manipulated. Even though BioNanorobotics is based on biological components, its proponents draw a boundary to demarcate it from medical applications. For addressing some of the challenges of bio components, researchers in BioNanorobotics use virtual prototyping and virtual reality technologies. Immersive environments allow for depicting atom-by-atom interaction and their interactions with the help of simulators (Ferreira & Mavroidis, 2006). The design of visualization and interaction for these immersive environments presents opportunities for HFE in BioNanorobotics research.

The third area of nanorobotics comprises of magnetically-guided nanorobotic systems. In this approach, the robot is a ferromagnetic object and is externally manipulated; i.e., the movement of the robot, actuation and propulsion, is achieved by an external magnetic guidance. Any changes in the robot location and direction of movement are manipulated by manipulating the field. Applications of external magnetic guidance are found in clinical Magnetic Resonance Imaging (MRI) applications (for e.g. see, Vartholomeos, Fruchard, Ferreira & Mavroidis, 2011 for a review).

Finally, nanorobotics uses concepts from nature to devise biomemetic robots. Researchers in this area try to mimic movement of unicellular organisms such as *E.Coli.* This bacteria has a number of molecular "motors" and uses its flagellum to swim. Thus, researchers try to mimic the movement pattern of these natural systems. Along with biomemesis, a related approach is taken to directly use the bacteria for locomotion and harness its capabilities for specific purposes (Fukuda et al., 2013).

Along with these above research areas, a working example of nanorobotics is found in the oil industry. The company Saudi Aramco has developed and tested nanorobots for mapping oil reservoirs (Kanj, 2013). These robots called Resbots (Reservoir robots) are injected into the oil reservoir. The reservoir rocks have tiny pores through which nanorobots can pass through (the width of 1/1000 of the human hair). Once injected, during their movement through the reservoir, these robots gather data on reservoir pressure, temperature, and fluid type. This data can be later used to manipulate reservoir properties to aid the flow of fluid. These manipulations, data gathering and new practices opened up by the new robotic devices provides opportunities for HFE in terms of human-robot interaction. Even though there are multiple new opportunities, the challenges are equally considerable in terms of robot movement and control that still need to be overcome for making nanorobotics a feasible and widespread endeavor.

6.1.3 UWNRG

> "In 2007, a group of undergraduate students undertook the task of designing a microrobot. Professors said it would take over 5 years and was the basis of several PhD theses. 4 years later the group had overcome the challenges and won the Microassembly Challenge at the 2011 Mobile Microrobotics Challenge, while being the only completely undergraduate team, as well as the only Canadian team competing."
>
> — UWNRG, 2014 (Accessed April 26, 2014)

UWNRG is an autonomous undergraduate student-run group. They classify themselves into four major categories: Administration, Technical groups, Control Systems and Non-technical groups. The administration consists of the project director who provides leadership and oversees the workings of the group. Every Tuesday, at 9:30 pm Eastern Standard Time (EST), the project director presides over the general meetings. In this general meeting, the groups provide an update of the work done in the past week and the work that they would accomplish in the coming week. The general meeting also serves as a forum for discussions of matters pertaining to the whole group. UWNRG is aided by faculty mentors. These mentors do not intervene in the day-to-day functioning of the group and will not be addressed in any detail.

The rest of the UWNRG team is divided into technical teams and non-technical teams. The non-technical teams consist of marketing and the business development team. The business development team arranges for funding, both internal to the university as well as externally; it also negotiates deals with prospective sponsors. The marketing team serves as the channel for communication about the team and its activities, as well as advertising about the team and representing it in many events. The marketing group also supports outreach activities in high schools, in events such as Technology, Entertainment and Design (TED) events, and other related marketing endeavors, in order to maintain the UWNRG presence in robotics.

Along with the non-technical teams, UWNRG has a number of technical teams: PAMELA, SAM, EMMA, SAW and MAYA. These teams are developed with different technologies but abide by a general understanding of robotics. For example, PAMELA is based on the principles of microfluidics; SAW on principles of acoustic propulsion; MAYA on principles of flux pinning; and SAM on magnetic actuation. All the robots are based on principles of control by changes in the surrounding external field. Thus, there are generic principles that are present, which each team actualizes based on the technology selected. Therefore, for this study, the robot MAYA was selected for understanding the functioning of robotics & UWNRG in greater detail. MAYA serves as a good example as it is geared towards the specific problem of microassembly of parts using robots. The problem of microassembly is a generic problem in nanorobotics (see Requicha, 2003; Neto, Lopes, Pirota, 2010). Further, work on the MAYA project began around July, 2013; thus, allowing for understanding the technical development from scratch. Since taking part in competitions is a crucial agenda for UWNRG, a brief discussion is provided concerning the challenges associated with the ICRA competition.

Another aspect of this study, mentioned earlier, is that of the challenges of classifying the robot. Typically, designing and fabricating a robot is considered a technical problem. However, as this study demonstrates, UWNRG is not only involved in building the robot but the entire robot ecology which serves as the backdrop of the robot. Thus, the challenge that UWNRG addresses cannot be understood in terms of technical dimensions, rather, the challenge is best understood in terms of its sociotechnical dimensions. The ecology of the robot is constrained by the rhythm of the academic life of the university. Since the students of this group are undergraduates and the work that they do for UWNRG is entirely out of their own interest, the academic schedule is a major constraint in their work. The academic exams and co-op schedules of University of Waterloo are a determinant to the UWNRG work rhythm. Over the past few years, the senior members of the group have identified heuristic work schedules based on ICRA competition and the UW academic schedules. These heuristics serve as waypoints for planning the robot design for the competition.

6.1.4 Details of the Fieldwork

In site 2, the research was conducted in two phases. The first phase consisted of interviews while the second consisted of observations and informal discussions. The interview phase was conducted over a period of four months (May, 2013 - July, 2013). Due to the shortage of time, the interviews were not completely transcribed but were referred to in cases of particular insights gleaned from the notes. The interview phase demonstrated the necessity for observation. Next, over a period of eight months (end of July, 2013 - first week of April, 2014), the weekly meetings of the entire group were attended as well as closely following the design and development of a particular robotic team, MAYA. The total official number of hours for this site was 50 hrs 45 mins (~51 hrs). The general meetings every week provided interaction with all the members of UWNRG who were on campus. This included about 20 students from September, 2013 till December, 2013 and another 17-19 (which included a few members from the previous months) from January, 2014, to first week of April, 2014. The official number of the design team that I closely followed included eight members. Due to the distributed nature of the group MAYA, only two to three members were on campus at any particular semester. Therefore, the meetings for MAYA were conducted online. I had the chance to interact with MAYA members who were on campus during the UWNRG General meetings.

6.1.5 Robot as a sociotechnical construct

To understand the robot as a social technical construct is to understand the social ecology of the UWNRG group. This consists of identifying the major processes involved in creating a stable environment, stable labor supply and appropriate amount of funding for devising the robot and taking part in competitions. In the rest of this chapter, the details of the process of achieving funding, making the robot and acquiring steady labor for the development of the robot are discussed.

6.1.5.1 Social Ecology of UWNRG

6.1.5.1.1 Process of Recruitment

The recruiting orientation for the academic year 2013-2014 was held on a Saturday afternoon at the beginning of the Fall Semester, 2013. The recruitment process is quite crucial to both the recruiters as well as the recruits. For recruiters, the new members should be able to actively participate and work on projects in the university. Thus, an important aspect of selection of the recruit is the motivation that the potential recruits display. The recruitment process is geared towards attracting motivated and talented people who actively contribute to the group. On part of the new recruits, UWNRG is conceived as a wonderful group which has won accolades, and provides a great opportunity for working in the area of Nanorobotics. The new recruits see the process as being a part of a major force.

Before this main orientation event, there was considerable promotion and advertising. This event was heavily advertised on UWNRG webpage; social media sites, such as Twitter and Facebook; and UWNRG members provided details to the frosh classes in various faculties in UW. To prepare for the entire recruitment, the general group divided the tasks among themselves. These included preparing posters, orienting for recruitment, orchestrating the event, devising questions for interviews, coordinating the interview schedule, arranging for the logistics involved in the interview process, i.e., arranging venues and schedules, among others.

The recruitment event consisted of a generic orientation talk about the group (Figure 6.1). This was followed by each of the technical and non-technical groups providing information about the scope and task of the team. A crucial point made by the UWNRG representatives is that the incoming candidates do not need prior advanced training in any area. Rather, UWNRG would provide training and hands-on experience. This approach helped to break down the hesitancy that potential candidates have while trying to understand how they would fit with teams. Also, UWNRG members stress the prospect of mobility within the group. Thus, a recruit may join the marketing group but can move to technical groups as vacancies arise. After the orientation talks, there was an open event in which the potential applicants could interact with the UWNRG team members. During the academic year starting Fall, 2013, UWNRG was looking forward to recruiting around 5-10 candidates.

Figure 6.1: Recruitment Session for academic year 2013-14. A large room was booked for the session. Each team provided detailed information about the activites

Once the applications were turned in, each application was first sorted and placed in a common folder, in Dropbox. UWNRG uses Dropbox, a file hosting service on the internet, as a common repository for UWNRG documents, which range from technical specifications to financial transactions. Each of the applications were scanned by each team and was later used to shortlist for an interview. The interview consisted of generic questions as well as logic puzzles, depending on the team applied for. Members of the technical teams also sat on business development team interviews as well as vice versa. The key idea was to gauge the motivation of the candidate as well as their overall fit with the team. Therefore, even though the applicants had applied for specific teams, they could be recruited for other teams.

Two main ideas drove the recruiting process of UWNRG. First, UWNRG as a group was not limited to engineers — entry was open to all disciplines. UWNRG members recognize that robotics not only presents a technical but a sociotechnical challenge; therefore, a multi-perspectival approach is important for the functioning of the overall group. Second, UWNRG members were recruiting people for specific teams but with a view towards the whole UWNRG group functioning. This view of the fit of the individual to the overall group also is demonstrated in the activities of the group. In general meetings, all the group members on campus come together for a common meeting. This approach ensures cohesiveness of the group as a whole.

Interviews and recruitment were run on a tight schedule as the academic calendar plays a highly crucial but invisible role in the functioning of UWNRG. Due to the realities of academic life; i.e., the exams, which loom large, the interviews were scheduled for a Friday, which also coincided with a course exam that was lighter than the rest of the nanotechnology frosh courses. Though the interview questions vary, an example of a question for the Business team interview involves asking the potential candidates to provide an impromptu sales pitch about why the candidates are a right fit for the group. This sales pitch allows the interviewers to gauge the speaking skills, benefits of sponsorships, as well as understand whether the participants have done background research on UWNRG.

After the interviews, the short-listed candidates were graded on a numerical scale and the applications of the high-rankers were discussed by the individual teams amongst themselves. The process of deliberation for choosing the right candidate was long and detailed. The members discussed pros and cons of each member in light of the project requirements, application summary and potential fit for the team. A key point for discussion was how particular candidates stood out from the rest of the crowd; i.e., applicant quality as well as how they could provide value addition to the UWNRG as a whole. Therefore, candidates who were overly focused on the ICRA challenge and traveling to competitions were systematically left out. The aim was to select candidates who were interested in robotics and providing value to UWNRG as a group. Entry into UWNRG is highly competitive. In all, for the academic year 2013-14, twenty-four applications were received. Fourteen applications were short-listed and after two rounds of interviews, seven candidates were inducted.

6.1.5.1.2 Maintaining Presence and Identity

An important part of UWNRG functioning is maintaining its presence in the broader arena of operations at UW as well as in the robotics community. The stance taken towards presenting themselves is highly professional. The UWNRG marketing team works hard towards representing UWNRG in various disparate events (Figure 6.2; Figure 6.3; Figure 6.4; Figure 6.5). These events include academic robotic conferences; undergraduate conferences; Technology, Entertainment and Design (TED) events; marketing fairs; as well as other outreach activities, such as high school robotics events.

In many of the marketing events, UWNRG maintains a booth with posters and flyers that advertise their robots and activities. The marketing team takes initiative in these activities by finding potential avenues and managing the associated logistics for the events. In the past, the marketing group has represented UWNRG in TEDxUW, 2011, to show its expertise in robotics. Similarly, they have also presented their research in Fusion, 2014, an event which is based on the integration of science and business. During these events, members of the technical team also accompany the marketing team members as they together provide a proper coverage and help describe UWNRG comprehensively. Along with maintaining presence of UWNRG, these marketing events also provide sources for potential connections. These connections are later followed on and developed further by the business group.

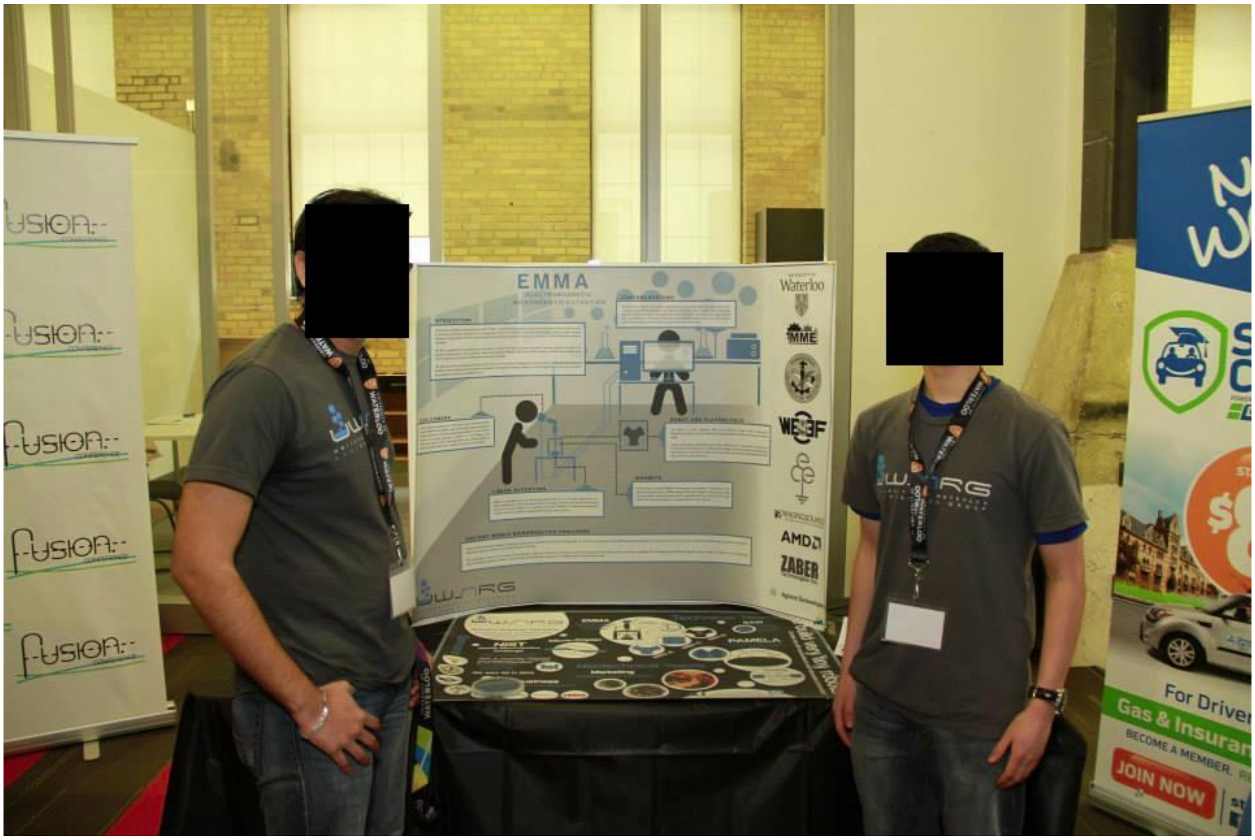

[redacted]
[redacted]

Figure 6.2: UWNRG Booth at Fusion Conference, 2014. One member from the technical team and marketing team were involved in this event. The members always wore UWNRG t-shirts during the event to maintain presence and group identity.

Figure 6.3: UWNRG marketing members explaining concepts at a trade fair

Figure 6.4: Close-up of the setup for display for a marketing event. The setup is arranged to identify the finer aspects of the scale of problems and challenges of dealing with this small-scale robotics.

Along with maintaining presence in the academic and business world, UWNRG tries to create value for the community through its outreach activities. In these outreach activities, the marketing team members represent UWNRG and spread information about robotics and nanotechnology in local schools in the Waterloo region. In this endeavor, UWNRG has collaborated with Canadian Coalition for Tomorrow’s ICT Skills (CCICT) to promote interest in engineering and nanotechnology in high school students. Even though the task of coordinating with high schools falls under the purview of the marketing team, the other students who are local to the Waterloo region help in contacting the schools and provide information regarding which schools would be receptive to UWNRG activities. Along with high school outreach activities, UWNRG has also promoted and presented at robotic competitions for elementary school students, such as FIRST LEGO robotics league competitions. Along with supporting high school events, the marketing team also organizes food drives and other related initiatives to maintain its presence in the broader community.

UWNRG maintains its presence in the university by arranging events that bring them into the spotlight. Such events include taking part in Frosh orientation events, such as student life 101; as well as arranging competitions, such as UW Nano-Olympics. In Nano-Olympics, there are competitions in which participants take part in challenges, such as making structures with Buckyballs, and winners are given prizes. Such events emphasize the identity of the group to a wider audience as well as maintain its presence in the university.

[redacted] [redacted] [redacted] [redacted] [redacted]

Figure 6.5: NanoOlympics organized by UWNRG . In this event the participants are involved in an assembly completion using buckyball magnets. The aims of these events are to maintain presence in UW community.

Picture courtesy: UWNRG website. Accessed: April 26, 2014

Presence maintenance in the wider community is only possible if the robotics group coheres internally. UWNRG members aware of this fact, enhance group cohesion by various measures. One such measure is having a common T-shirt with the UWNRG logo on the front and sponsor logos on the back. These T-shirts provide a common outlook during marketing events. Further, to maintain group cohesion and the spirit of camaraderie, the marketing team arranges events where people get together and take part in common fun activities.

Along with formal methods of identity and presence maintenance, UWNRG senior members often describe to new recruits what UWNRG as a group aims to accomplish. This happens through the general meetings as well as group meetings. There is no specific agenda set for explaining the identity of the group to new recruits. Rather, it is a process of slow diffusion gained from the apprenticeship mode and on-the-job learning process. At times, when the need arises, the group/team leader clarifies certain ambiguities and highlights what UWNRG identifies as a group. The process is highly democratic, as the members propose, dispose and critically examine the ongoing situations to chart a course for the future activities. Also, after certain intervals, the group leader meets with the team leaders and decides upon team directions and future strategies — technical as well as non-technical. For example, there was an effort to devise a mission statement for the group. Team leaders along with the marketing leader spent a considerable amount of time reflecting on a proper mission statement. At the end the process was made democratic. All the members were asked to provide their ideas and opinions, and later these ideas were put together to form a mission statement that reflected UWNRG identity. This example reveals the flexibility in UWNRG functioning. Further, it also shows that the identity of the group comes about from the senior team members but is also democratically conceived in the process of everyday activities.

UWNRG also maintains its presence in lab meetings of the laboratory whose clean rooms they use for fabrication. Even though attending the lab meetings is not required of them, UWNRG sends its members to these meetings. The physical presence in meetings ensures that UWNRG’s efforts in devising robots are known to the other members of the weekly meetings. The physical presence also allows them to maintain cordial relations with graduate students of the laboratory. A few graduate students supervise the work of UWNRG members in the lab and provide support by discussing the procedure for fabrication or suggesting alternate routes for achieving successful results.

6.1.5.1.3 Developing stocks of knowledge - Technical and Project-related

A major aspect involved in UWNRG functioning is developing stocks of knowledge and figuring out potential lines of activity. Knowledge acquired by UWNRG members has two components. First, there is knowledge required for the design and fabrication of the robot. Second, there is surrounding information that provides knowledge about where to get access to certain equipment on facilities for their fabrication process. From the initial design concept to a working robot represents a huge leap. This requires understanding knowledge about materials and equipment that will be required in the intervening steps. To make this leap, UWNRG members constantly research on the topics they are addressing. For example, in the team MAYA, each member aimed at becoming an “expert” in a particular area of the robot they were making, i.e., one member focussed on the material and all its associated properties, the second focussed on the process of sputtering the wafer with particles of another material, and so on and so forth.

Essentially, while there is considerable support on the design direction and fabrication, it is the new recruits who act as the appendages for the whole group. This is due to the fact that many of the team members are off campus (typically in industries and research laboratories) working on co-op programs. The co-op program in nanotechnology engineering lasts first for two four month work terms, and later in the program, for two eight month work terms. As many of the technical team members are from the nanotechnology engineering program, at any given semester, almost half of them are out for co-op. For example, in MAYA almost half of the members were off campus for the two semesters over which this study was conducted. In Fall semester (Sep-Dec, 2013), three members were handling the daily requirements of the project. In the winter semester (Jan-Apr, 2014), one member was replaced by another. This schedule requires that members of the group have knowledge that is overlapping among each other. It also requires an understanding of project requirements so that all the members have a considerable insight and depth of knowledge. Thus, as previously discussed, in the process of recruitment, potential candidates are selected based on with the overall fit with the team as well as the group as a whole.

Along with developing knowledge about the robot, a considerable stockpile of information is actually required to fabricate it. Fabrication in this case is not simply a technical process.

Fabrication requires lab facilities and access to equipment. Since each robotic team is unique, it requires a different fabrication procedure. Not all of the equipment is available at one facility. Therefore, UWNRG technical team members require information about equipment and its presence in the UW academic community. UWNRG mentors sometimes provide directions as to which potential members of the UW academic community could be contacted. Such type of knowledge about whom to contact and what kind of equipment is required is essential to UWNRG functioning. Over the years, UWNRG has created a stockpile of knowledge pertaining to equipment and the potential access to it.

Similar to fabrication in site 1, operating equipment for fabrication requires considerable knowhow. Therefore, a lot of knowledge involved in the process is actually knowledge of lab equipment and also knowledge of access points in the UW academic community, who would allow use of their lab facilities. In many cases UWNRG members seek the help of graduate students of the lab in which they are working. This is because the equipment required for fabrication is extremely expensive. However, UWNRG students aim to understand the process well enough in order to work with less supervision on future projects.

6.1.5.1.4 Communicating knowledge within the group

Development of stocks of knowledge goes hand in hand with communicating this knowledge to new recruits. In weekly meetings, the senior members of teams often discuss the strategies and work to be done for coming week. This meeting provides a forum for exchange of information. It also serves as a formal process of guidance provided by the senior members of the group. Some aspects of discussions could include guidance on how to approach members of the academic community who will provide access to lab facilities; how to deal with graduate students; how to follow up on emails with professors who may be too busy to reply; and how to gel with members in the lab in which they would be conducting the fabrication of the robots, among other things.

Every year, UWNRG trains 2-3 people to work in a clean room facility for developing robotic fields for the competition. Fabrication involves a considerable amount of dexterity and knowledge of equipment (with similar characteristics to the process identified in Site 1, chap 7a). Since they are using other people’s facilities, it also requires making connections with people as well as maintaining presence. Due to the academic schedules of UW, often trained members are unavailable, therefore, there is a constant demand for properly trained individuals who can work in the lab facilities. Senior members arrange time from their schedules to guide the new recruits through the process of fabrication. This allows for transfer of knowledge based on the apprenticeship mode of working. The nature of dexterity required for the fabrication process, along with the academic schedule makes the transfer of knowledge to new recruits a considerable source of challenge for UWNRG as a whole.

The apprenticeship mode is a more generic theme in UWNRG functioning. The business development team trains its new recruits in a similar fashion. For this team, training involves mock sessions where the recruits present a short proposal as if they would be presenting to prospective patrons. This speech would ideally begin with past successes of UWNRG. A special emphasis is placed on the fact that UWNRG is an undergraduate team competing with graduate students. In the speech, the use of acronyms is specifically avoided and the speech is kept at a very high level emphasizing conciseness and avoiding details unless specifically asked. During these mock sessions, critiques are provided by the team members. There is considerable amount of learning based on one's mistakes as well as from mistakes of peers. Along with presentations, proposal writing is also taught to new recruits of the business development team by apprenticeship.

6.1.5.1.5 Career contingencies of members

A new recruit has considerable opportunities for growth in UWNRG. First, there are chances of mobility from non-technical teams to other teams. Also, in many cases, technical team members are involved considerably in marketing events as well as in meetings with prospective sponsors. This mobility offer the new recruit considerable overall development. Thus, a new recruit learns many new skills by apprenticeship and on-the-job training. Recruits who show considerable achievements in their work are considered for team leader positions when the opportunities arise. Thus, this provides upward mobility as well as newer vantage positions for understanding robotics. Based on the performance of new recruits, one of them is selected to represent UWNRG in the ICRA robotic competition. This decision is made by senior members of UWNRG through a democratic process. Along with these opportunities, management of

UWNRG activities and academic/co-op requirements proves considerably challenging for many recruits and there are cases of attrition, where members drop out due to their priorities and related academic workload.

6.1.5.1.6 Handling deviance

The functioning of UWNRG depends on the work of its members. It is a democratic group with the members being involved voluntarily. The group has the aim of designing, fabricating robots and competing in teams. In weekly functioning, the locus of activities of the group is bound by the group and team leaders in light of the future goals of the group along with its identity. For example, every year fresh batches of recruits are new members to the group. They provide new perspectives and ideas. These ideas are discussed and democratically accepted or rejected by the group. This contributes to a culture of democratic assignment and handling of particular members who try to steer the group towards new ideas that may not be conducive in the functioning of UWNRG.

Identity of the group is dynamically balanced by the goals of robotics design as well as the voluntary support of the members. Since there is no external pressure, the group functions only if the members, who are assigned certain tasks, complete them in time. In many instances, due to academic schedules, certain members face considerable challenges in trying to balance their schedules.

In contrast to the above, there are also many members who do not contribute to the group meaningfully. UWNRG constantly takes stock of its members and its activities in a democratic manner. This is done by the group leader and the team leaders having discussions on generic aspects pertaining to the group. For example, in the beginning of the academic year (2013-2014), after winning the competition, UWNRG was heavily restructured. Members were given an ultimatum regarding their role in the group and also to reassess their priorities. If they hadn’t contributed meaningfully to the group for the last six months, they were given a choice of continuing with the group if they would contribute in the future. The entire process was generic and not made specific to people identified on a case-to-case basis. Many members recognized that they were not involved, or did not wish to be involved with the group in the future. Thus, this was an effective check to handling the members who were deviating from the dynamic norms of the group.

6.1.5.2 Funding robots

Robotics design, fabrication and research involve considerable cost. The funding of the group is handled by the group and is crucial to the final product. Acquisition and use of funding from various sources requires three main aspects. First, there is a necessity for finding patrons who are ready to support the group in cash or kind. Second, there is the necessity for maintenance of reciprocity with these patrons to obtain funding for later projects. Finally, the funding received has to be put for proper use to support UWNRG's technical projects.

6.1.5.2.1 UWNRG and its patrons

Patrons for UWNRG belong to diverse groups. In general, they can be classified in terms of Business Corporations, University of Waterloo Engineering Departments, Professional Engineering Societies and Local funding agencies connected to UW.

The process of getting new sponsors is initiated by contacting them by emails. A member of the business team searches on the internet and identifies potential sponsors. At this stage not getting a response is quite common. Therefore, the business group tries a follow up phone call on the number listed on the website. The members of UWNRG realize that physical presence is vital for obtaining patronage; i.e., they are not any other student group sending emails. In case of local sponsors, UWNRG members often present their projects to the sponsors. Physical presence allows them to have a greater impact on the potential patrons. For international members having a physical presence is difficult, therefore, emails and phone calls are the only possible choices.

A standard project presentation contains a background of the group. Past successes are highlighted, technical projects are briefly discussed, the role of the design, fabrication and research are described, future endeavors are outlined and request for funds in cash or kind are presented.

Typically, the business group members take individual initiative in keeping in contact with funding agencies. Therefore, if a team member gets a corporate sponsor, then that person is in-charge and serves a point of contact for any future contacts with the group. These engagements last as long as the person is a part of the team. Therefore, even if the person moves from the business development team to any technical team, they still remain the point of contact for the particular patron.

Many contacts do not materialize into proper funding relationships. Thus, potential contacts can be divided into three main categories. The first category is of those who directly deny any further involvement. The second is those who show no interest by not responding. The third is those who respond and ask for more information; thus, opening a channel for communication. This third category of sponsors is comprised typically of groups who can support UWNRG in cash or kind. Cash is preferred, as it allows for easier mobility and provides the groups the possibility for investing it in buying chemicals for fabrication. In many cases the patrons provide support in kind. These patrons who provide support in kind typically provide renewed services. For example, after a few years of service, the actuator setup for the robot malfunctioned. The patron supporting the actuators promptly provided a new set of actuators.

The university labs where the robots are fabricated serve as an important site for providing support. For example, when a small amount of chemicals is needed, then the lab supervisors allow the use of existing chemicals. Patronage also is provided by certain members of the UW community. One member had some laboratory space which was generously provided to house the UWNRG equipment. Apart from these patrons, there are other cases where the funding is a mix of cash and kind. One sponsor initially acquiesced for providing cash but as the discussions continued, finally provided a mix of cash and licensed software.

Along with corporate sponsors, the university and its constituent groups are supportive in terms of providing money for research and travel. The travel to the robotic competition, ICRA 2013, was generously supported by a number of members and governing bodies in the university. For the requirements on a semester basis, UWNRG also applies to local funding agencies connected to UW, that provide support for undergraduate student initiatives. Based on the support that patrons extend, they are divided into categories of gold, silver and bronze sponsors; with gold members providing the highest amount of sponsorships.

6.1.5.2.2 Achieving reciprocity with patrons

UWNRG endeavors to maintain a rapport with the patrons. After every competition, the UWNRG extends its gratitude and sends a letter of acknowledgement to every patron. The details of the competition are provided and the UWNRG’s position in the competition is highlighted.

In everyday activities, UWNRG also supports their sponsors by using webpages and social media, such as Twitter and Facebook, to emphasize the support provided by the sponsors. Latest happenings in the news about the sponsors are also highlighted in the Facebook page and UWNRG’s Twitter tweets. In order to maintain a proper relationship, after having received support from a patron, UWNRG sends a plaque to extend their gesture of appreciation. Sponsors expect that UWNRG does what it claims to do; therefore, sending reports, updates and constantly following up with the sponsors maintains the reciprocity of patronage.

Of crucial importance to the sponsors is the necessity for understanding how their products have provided value addition to the team. Therefore, in the media and press announcements, UWNRG explicitly highlights the generous support provided by their patrons and how their patronage has helped UWNRG. UWNRG also attempts to go an extra mile to extend reciprocity to their sponsors. For example, in one case, the patron provided a licensed software and a cash amount. Even though the software that was provided did not fit in with the current UWNRG setup, nonetheless, UWNRG members did try to incorporate the software for a very small part of their project work. Thus, showing the applicability of the software to the client and ensuring future support.

However, sponsors are not always benign and quick in their response. In one case, UWNRG had an agreement with an electronics company for parts. However, a number of times when a specific product was ordered, the parts arrived quite late as well as were not as per requirements. As a result, the parts had to be reordered from a different vendor.

Funding, however, is not a straightforward process. For example, certain sponsors do not fund perishable objects and materials. Chemicals, being perishables, fall out of the domain of their funding. Thus, in the case of silicon wafers and the associated chemicals for fabricating the robot, there remains considerable ambiguity. Silicon wafers are chemical products that would be etched and used for the design of the robot playing field for the competitions. Therefore, they are a crucial component of the final robot. However, technically they are perishables with a shelf life of two years. Building a case for the necessity for funding silicon wafers as durables, and hence as worthy of patronage, was a considerable challenge for the business development team, as they had to show the value of requested funds contributing to the final robot.

6.1.5.2.3 Managing the funding

In order to receive the funding obtained from various groups, UWNRG has an account under the aegis of the Mechanical and Mechatronics department (MME), UW. This account serves as a central repository for UWNRG and an MME staff member takes stock of all transactions through this account. In case of cheques, patrons are requested to make a donation to UWNRG on the university address. This process ensures complete transparency in the funding process.

The account balance is maintained by the MME staff member and is available for the UWNRG business group at any time, as needed. Along with this external balance, UWNRG maintains an internal track of its financial status. This tracking is not always straightforward as many members forget to send a copy of the reimbursement receipts to the person tracking the financial flow internally. As a result, in the most recent case, there was some confusion while the UWNRG members tried to balance the account books internally. As a result, typically after certain months, the group tries to account for all its expenditures and keep the records intelligible for future transactions. All financial documents are shared at a common software repository and are available to only a selected few people.

Typically, once the money is available, purchases are made. Individual teams order the required materials and parts and are later reimbursed, based on the receipts. Equipment and materials are only brought after considerable deliberation among the members and in light of the budgetary constraints. Generally, the technical team provides the specifications of the devices that are needed. However, at times, in terms of more generic requirements, such as laptops and USB ports, the business development team makes the appropriate purchases based on budgetary constraints.

Funding is severely constrained in many instances and certain sponsors levy terms and conditions. For example, in case of requesting funding from a university based funding body, UWNRG requested funds for a laptop for image processing work. As a result, they were provided CAD$ 700, which was less than what was requested. A good laptop for image processing would require about CAD$ 200 more; therefore, UWNRG requested for the sum in the next semester. In this semester, they were denied the extra funds. This resulted in the fix. Either UWNRG could wait for another semester to apply for the funds or buy a cheaper laptop. In a mutual discussion, one member highlighted that in a given academic year, the committee members of the afore-mentioned funding body remains the same. Therefore, if they were denied the CAD$ 200 in a particular semester then they would be denied the same for the next semester. Further, if they waited for too long, then there would be chances of expiration of the funding as well as questions that would be raised by the funding body about the expenses. If the previous funds are shown as unspent, then UWNRG would not be given further funding and asked to spend the money they already have in their account. Thus, managing funding poses several challenges as well as requires proper maintenance of reciprocity with the sponsors.

6.1.5.3 Making robots

The central problem in microrobotics is that of power and control. Typically, large robots at the macroscale have onboard power and internal-based control. However, with robotics at the extremely small scale, these problems become increasingly insurmountable. Under the broad rubric of the twin notions of power and control, UWNRG develops multiple robots using different technologies, ranging from microfluidics to MEMS. By taking into account multiple technologies, UWNRG attempts to address robotic power and control from a broader perspective.

In this chapter, I will focus on a specific robot MAYA. Work on the robot MAYA began in late July, 2013 and I was able to follow the development of this project till the end of March, 2014. The project demonstrated the sociotechnical challenges that the team faced in conceptualizing and developing a robot. MAYA stands for Micro-Assembling YBCO Apparatus. YBCO is Yttrium Barium Copper Oxide, a superconducting material. Superconductors display some unique properties when placed in a magnetic field, i.e., they bend the magnetic field around it (Type I superconductor) or let a part of the magnetic field pass through it (Type II superconductor). Therefore, if a Type I superconductor is placed over a magnet, it will float over it. Whereas, in case of Type II superconductor, the magnetic field can penetrate the superconductor at certain sites giving rise to passages (flux tubes) that allow the lines of magnetic flux to pass through. The flux passing through the flux tubes pins the superconductor to a specific place in the magnetic field. This phenomenon is called flux pinning. In order to move the robot around, the magnetic field can be varied through the flux tubes to achieve proper actuation and control. This idea of flux pinning is the main concept behind MAYA's conceptualization.

MAYA was specifically designed for a microassembly task. In microassembly, the robot needs to assemble various parts in a particular pattern. In order to complete the microassembly task, MAYA was envisioned as having a thin substrate with a claw attached to its bottom. The analogy of MAYA was that of a "box tent", a small plastic table to prevent the top of a pizza box caving into the pizza. Due to the analogy of the claw-like appendage connected to the bottom of the base, MAYA's interim name was Quantum Claw. However, UWNRG has a tradition of having robot names as people's names: SAM, EMMA, PAMELA, among others. Therefore, after much deliberation and creative discussion over the course of one entire meeting, the name MAYA was devised.

Once conceptualized, MAYA was separated into two challenges - development and control. The initial focus was on development; therefore, control was left as a problem to be handled later. The robot development was further divided into two parts. Based on the structure of MAYA, it was decided that the team would focus on building the tabletop; i.e., achieving a flat superconductor block that would be amenable for the purpose.

Making YBCO materials required a sputtering procedure as well as use of special equipment. MAYA team members were searching for this equipment and their academic mentor provided a reference to another professor who had the relevant resources. After a delay, MAYA members came to know that the faculty member, who had the equipment, was away from campus on a sabbatical leave. However, this faculty member provided a link to his colleague whose lab had the relevant equipment. Finally, MAYA members found access to the equipment they needed.

While the search of the equipment was being conducted by the members on campus, the off campus members were conducting research on finding papers and methods that would enable them to formulate a procedure for fabricating the robot. Making a superconductor was not a straightforward process as the straightforward step-by-step procedures are rarely provided in detail in academic research papers. Commonly, in many research papers the procedure is discussed at a higher level description. However the fabrication procedure for the specifics in the laboratory has to be developed stringently and posed a challenge for the MAYA team. In the first two months of Fall, 2014, the idea of MAYA was conceptualized and the details of the chemicals required were addressed. The cheapest price for the chemicals was sought. For example, strontium titanate would be a good choice but is extremely expensive. In contrast magnesium oxide is cheaper but presents challenges in the fabrication process. Further, since the process was not completely developed, other courses of action were also ruminated upon. For example, they could make a small batch of superconductors from magnesium oxide and check the crystalline structure and, based on the results, decide whether to invest in more expensive strontium titanate. Along with these decisions, they were also creating a prospective list for chemicals, devices and equipment that they would need for complete setup for MAYA.

The design process is inherently laden with ambiguity. It can be best characterized as a process that develops with an end goal in the vision of the MAYA team. The ambiguity arises out of several sources ranging from the lack of knowledge about the process, materials and the possible access to equipment. Further, there are considerable delays due to people not responding, or difficulties with coordinating with graduate students for lab access. These various delays contribute to the development of the robot. Till March, 2014, the equipment had been located, lab access gained, and some of the material had been ordered. With the onset of examinations in April, 2014, work on the MAYA project was halted and was expected to begin in May, 2014 with the fabrication of YBCO.

6.1.5.3.1 Preparing for the competition

The ICRA competition has two challenges. First is to navigate an obstacle course in the least amount of time and the second is a microassembly task; i.e., the robot is used to move and assemble certain parts into a pattern. To address these challenges, UWNRG uses a hybrid method of controlling the robot. For the obstacle course for navigation, the process has been automated with no human intervention. For the microassembly task, the process requires considerable human intervention in controlling the robot. This type of human-robot interaction for microassembly holds implications for human-robot interaction and interface design.

Along with MAYA, two other robots, EMMA and SAM, are briefly mentioned as they are used by the UWNRG team for the robotic competitions. EMMA has won robotic competitions in the past and SAM is the most recent competition robot for ICRA 2014. Both these robots are based on magnetic principles. The robot in itself is a small piece of ferromagnetic material which is controlled by a changing the surrounding magnetic field. The robot of the competition completes its challenges on a playing field. Both the dimensions of the robot and the playing field are provided by the competition organizers (Figure 6.6; Figure 6.7; Figure 6.8; Figure 6.9).

In EMMA (ElectroMagnetic Micro Actuation), a magnet was placed on a set of actuators that provided the movement of two axes, perpendicular to each other, on a horizontal plane. Thus, the analogy of the movement of EMMA is that of having a iron piece above a sheet of paper and a magnet below it. Once the magnet is moved below the paper, the iron piece above it automatically follows (Figure 6.10; Figure 6.11; Figure 6.12; Figure 6.13).

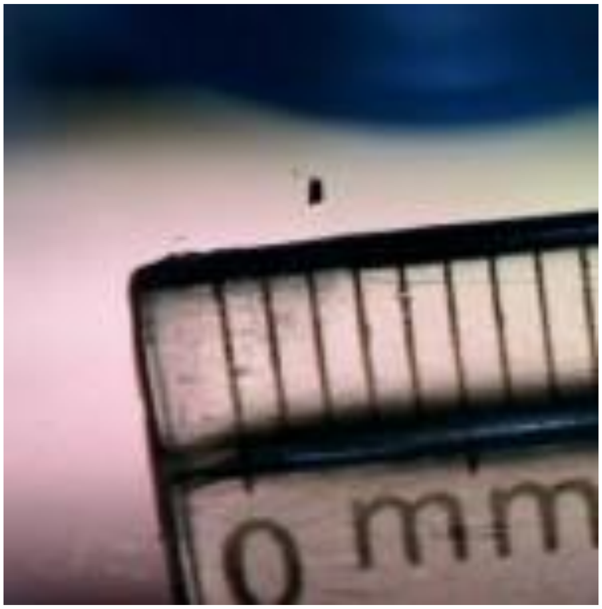


Figure 6.6: Size of EMMA as compared to the everyday space of knowing and acting

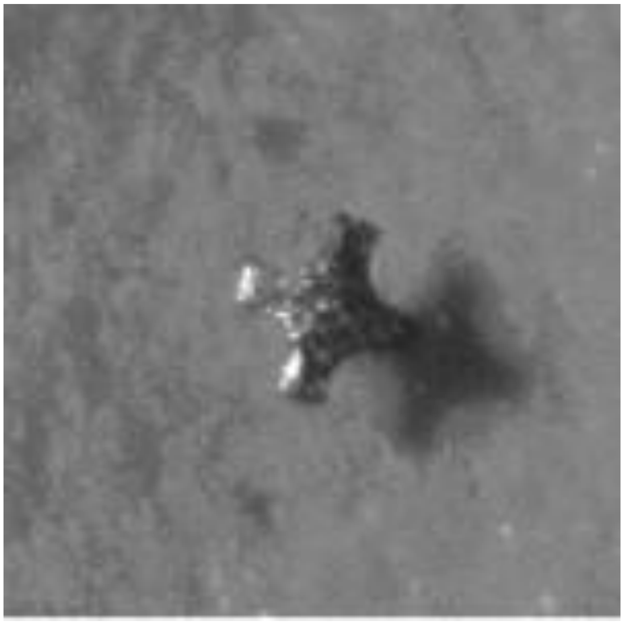


Figure 6.7: Close-up of the robot EMMA

Figure 6.8: Close-up of the playing fields

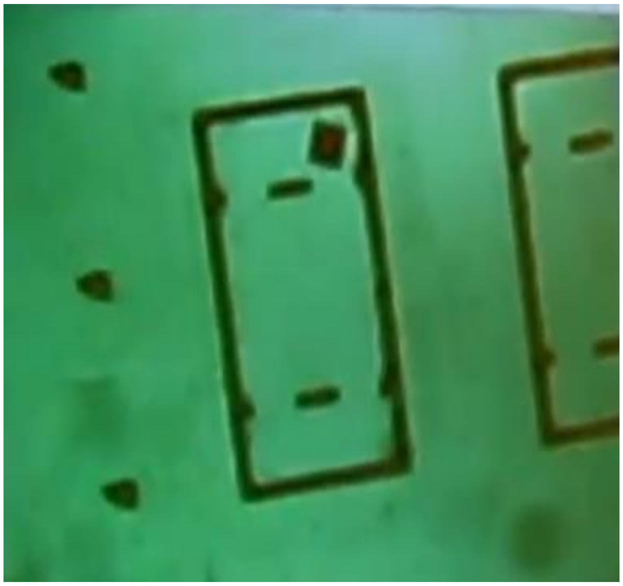


Figure 6.9: Robotic playing field under the microscope, ICRA, 2013

Picture(s) courtesy: UWNRG website. Accessed: April 26,2014

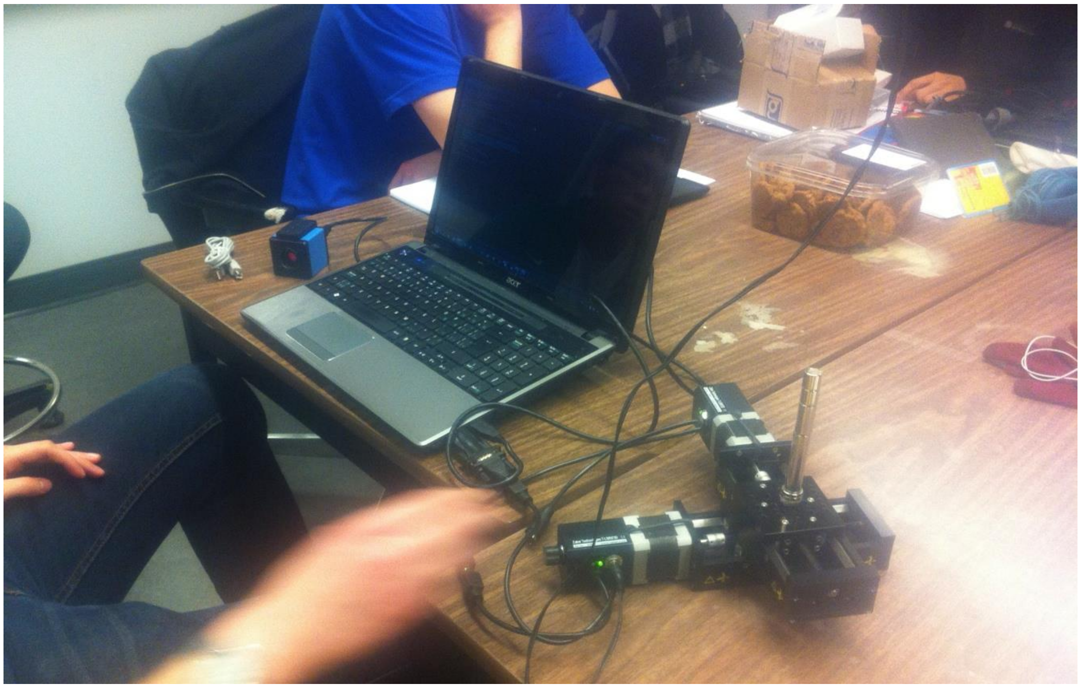


Figure 6.10: Cameras and actuators being tested for EMMA setup. The members of the control team test the actuator functioning with the software code written in python to ensure smooth functioning of the robotic control setup.

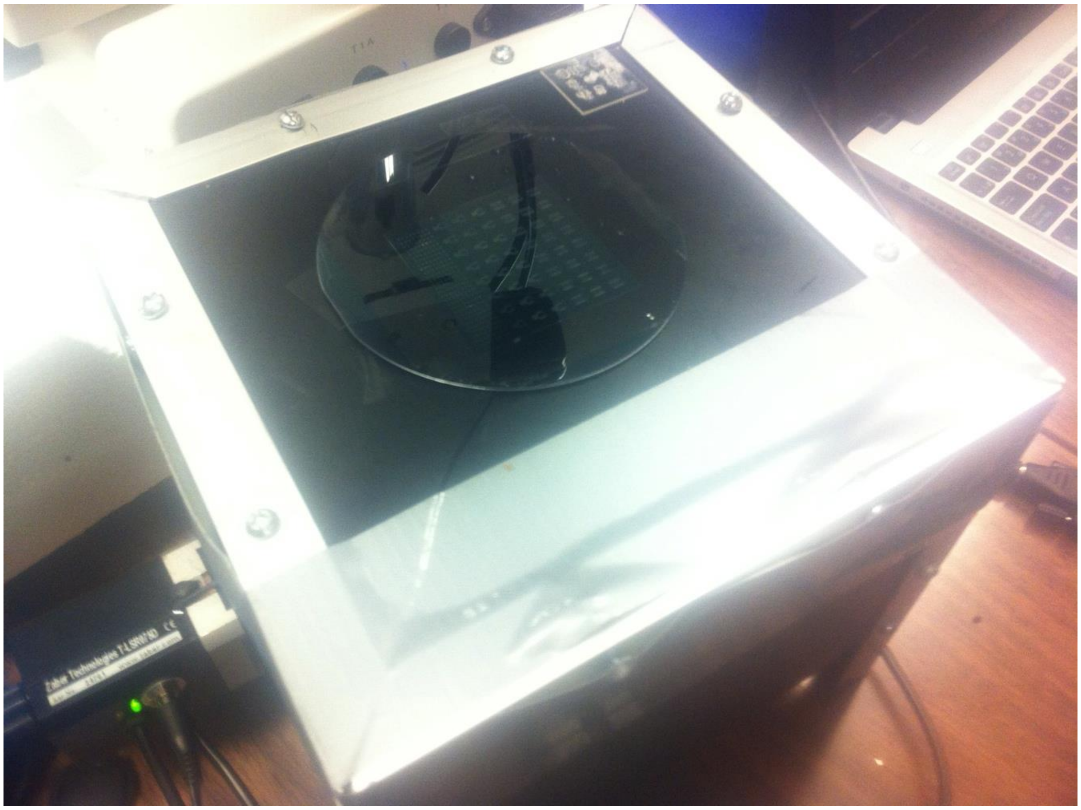


Figure 6.11: Playing fields for EMMA setup for ICRA competition 2014. A large number of fields are etched on a single silicon wafer.

Figure 6.12: EMMA setup being prepared for the completion for 2014. The actuator is below the robotic playing field. The microscope is above the playing field. Both the microscope and the actuators are connected to form a closed loop setup.

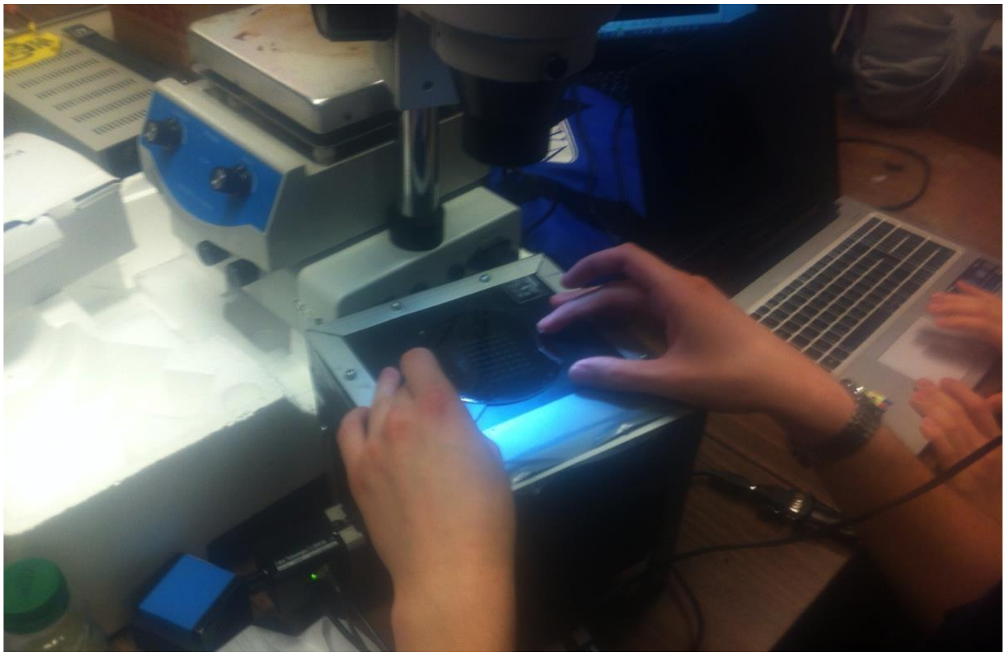


Figure 6.13: Playing fields being tested by a painstaking process of visual inspection by shining a light and checking the individual fields if they are properly formed.

Even though EMMA won prizes in robotic competitions, UWNRG members found certain drawbacks that could be improved upon. First, since the magnet on the actuators was pulling the magnet downwards, it contributed towards a frictional force in the robot movement. Second, in the actuator setup, they wanted to send controls at a speed faster than the present actuator could react. Therefore, to circumvent both these limitations, they devised a new type of robotic control setup (Figure 6.14; Figure 6.15). In this control setup, the force acting on the robot is parallel to the surface on which the robot is present. Further, the control signals are provided by changing the magnetic field by fixed electromagnets. Therefore, by reducing the mechanical movements, the robot controls have been made faster.

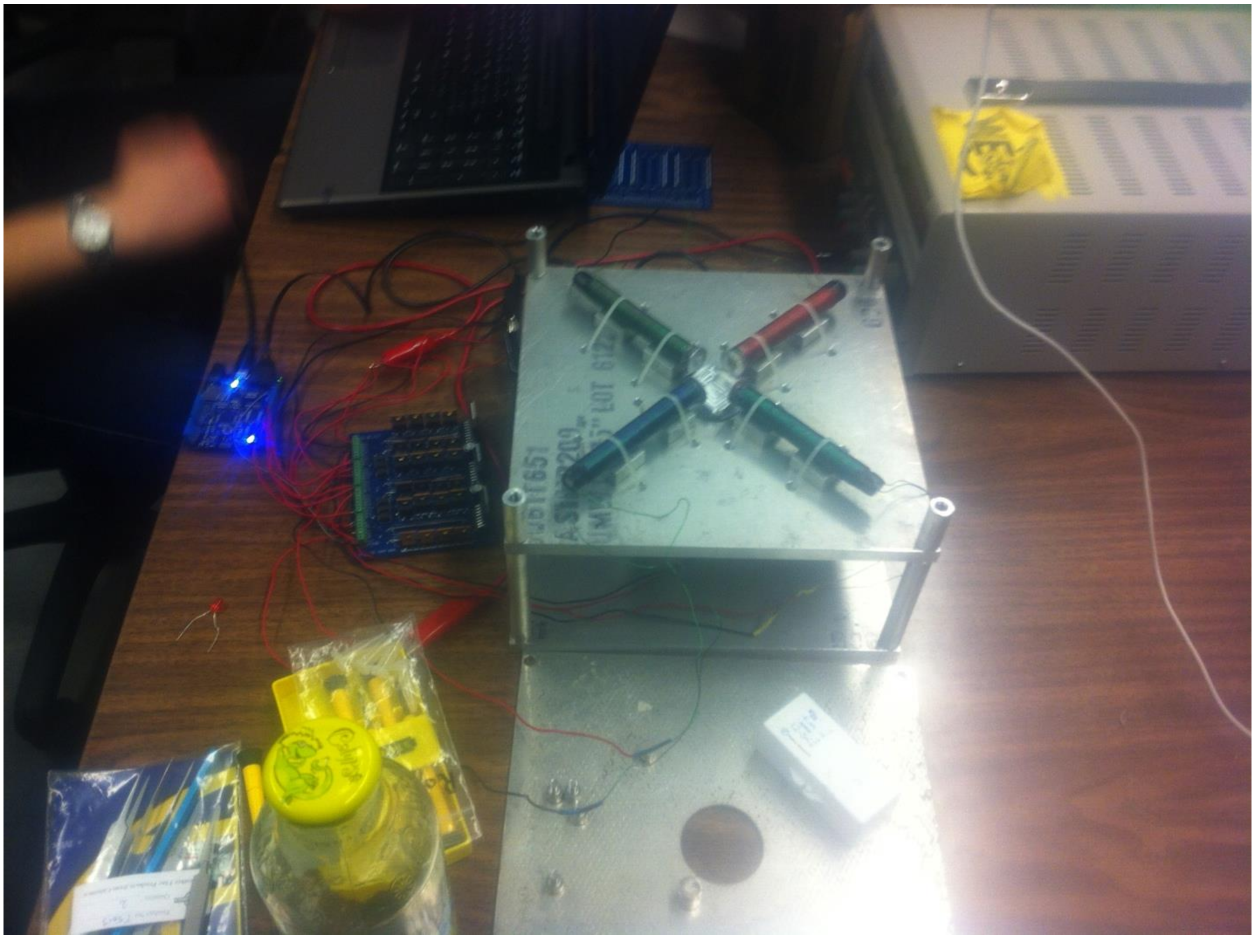


Figure 6.14: SAM setup for ICRA completion 2014. An alternative setup is arranged for a new robot SAM that is prepared for future competitions. At any given year, UWNRG has a main robot being developed for the competition as well as a backup robot.

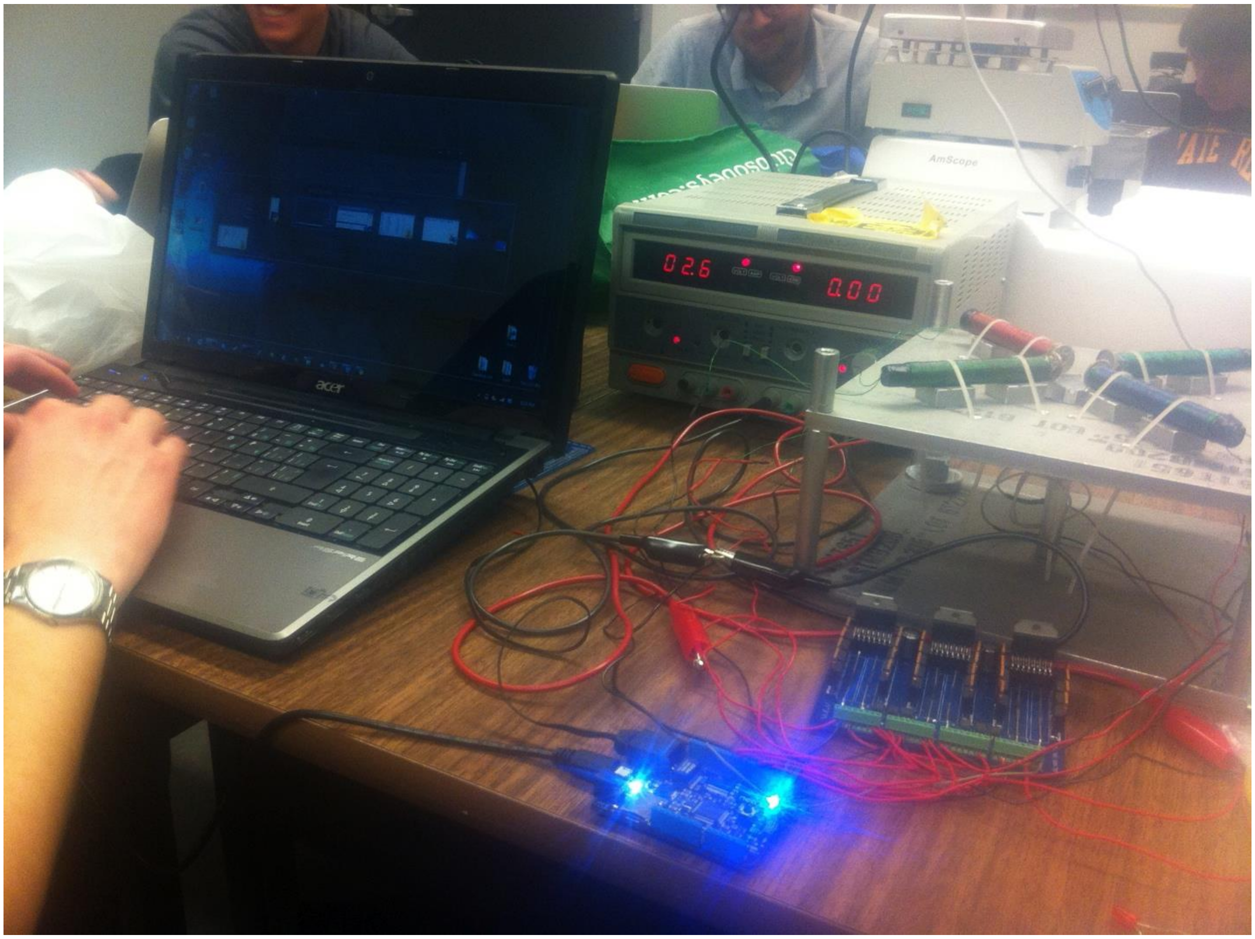


Figure 6.15: SAM setup being tested for ICRA competition 2014. The backup robotic setup is tested properly along with the main robot for the competition.

To successfully take part in competitions, the technical considerations are at times painstaking. The robot fields are etched on silicon wafers. In one silicon wafer, there are many small fields based on the contest specifications. During fabrication, not all the fields are properly developed. Thus, having a large number of fields ensures that there is no paucity of good fields. Each field has to be carefully tested before the competition. Testing the fields visually, under the microscope, as well as with the robot is a methodological and painstaking process.

Along with the fields, the robots are no less problematic. They are literally at the extreme edge of the human vision. Since they are magnetic, they often clump together and are visible in a mass. Separating them and singling them out takes an extreme amount of care and patience.

Further, each robot is extremely expensive, often costing around CAD$ 30-40. Since each of them require extreme care, the members testing the robotic setup use micro tweezers in order not to damage them. Other similar equipment also work for this purpose. Some members prefer using a business card to scoop out the robot. In one case a member testing the robotic setup used a white sheet of the paper with the robot placed on the workspace where the robot would be placed in interim, while not being tested. The white sheet provided the necessary contrast for the small, almost negligible, speck of the robot (Figure 6.16; Figure 6.17; Figure 6.18).

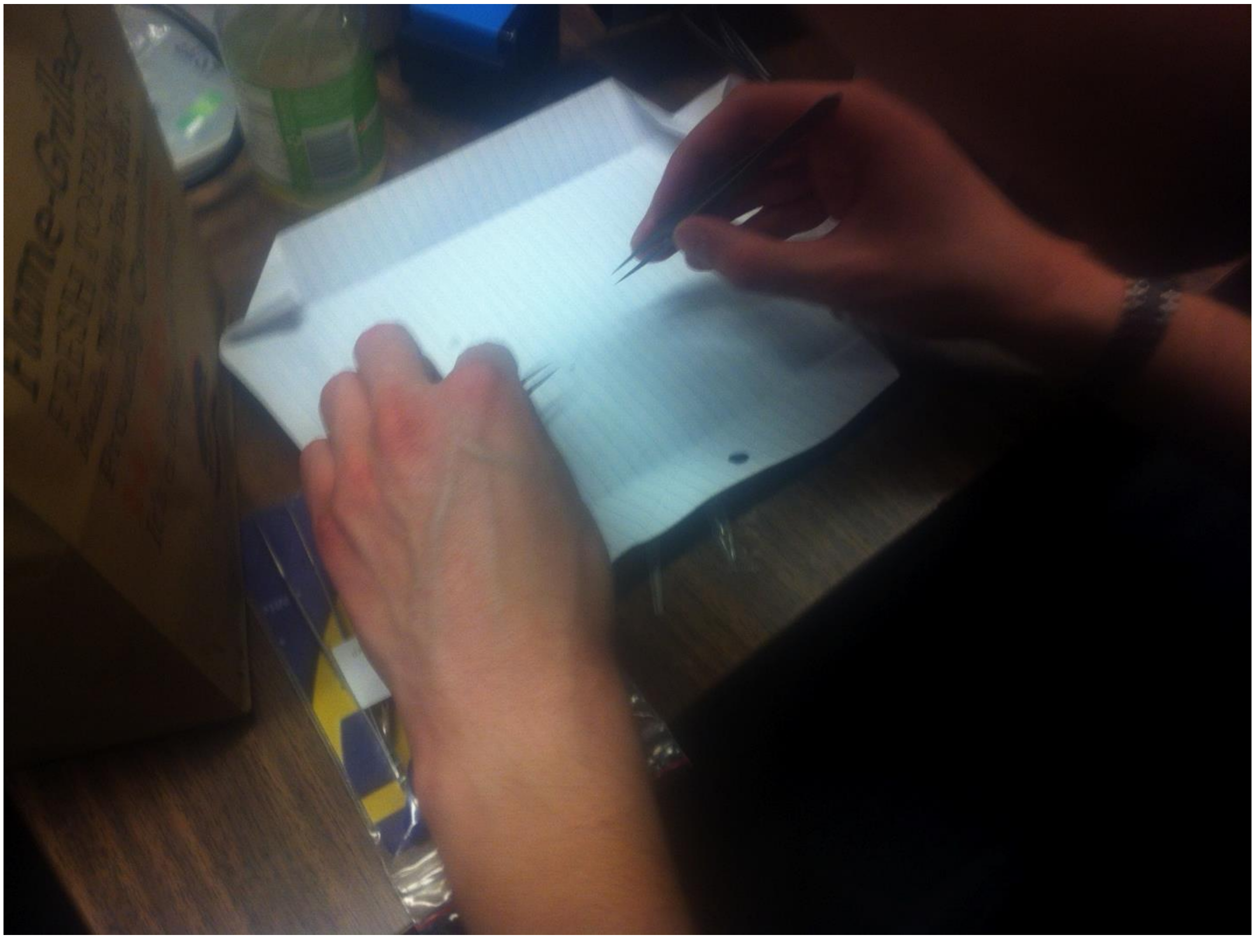


Figure 6.16: Using Micro tweezers and a white sheet of paper to make the robots visually salient. During the testing process, the robots being small, tend to get lost. Therefore, during the testing process, they are placed on white background (paper) to make them visually salient

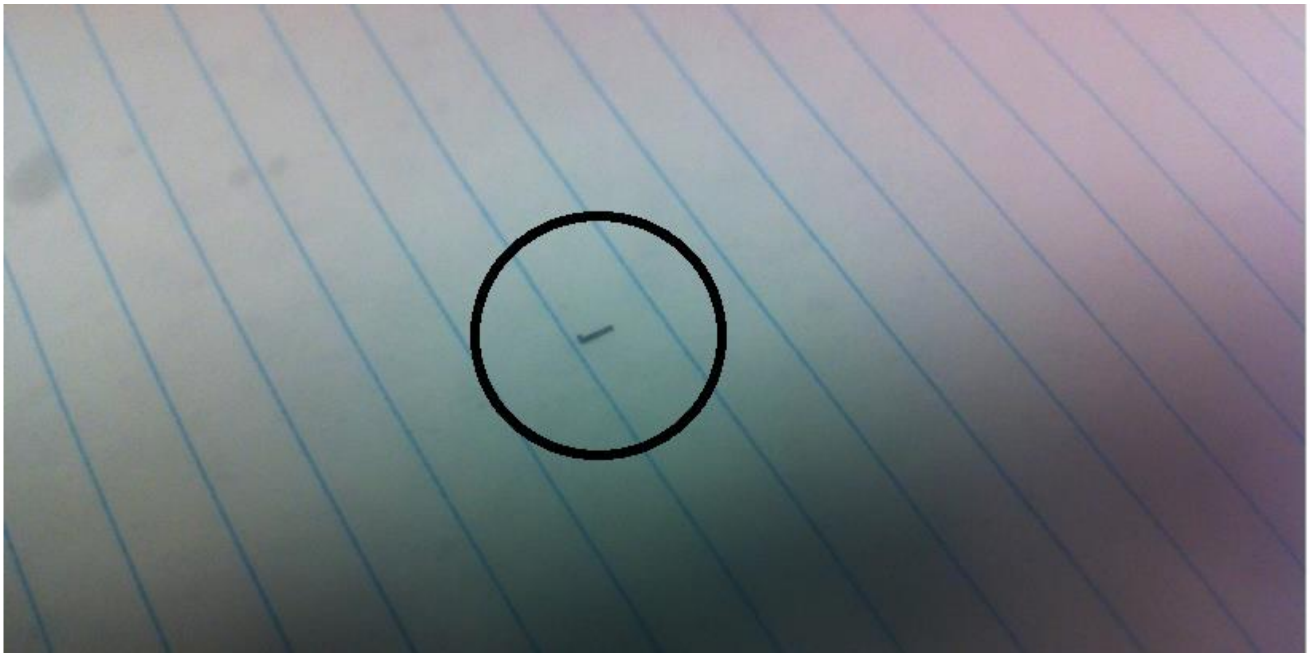


Figure 6.17: Close-up of multiple robots clumped together on a white sheet of paper

Figure 6.18: Multiple robots clumped together in plastic containers. The whole bag is roughly worth CAD$ 500-600

Dust forms a major challenge in the robotic competitions and UWNRG ensures that the fields and the robots are kept clean and dust free. However, with the new setup in SAM, UWNRG has tried to enclose the robotic playing field with glass that would prevent contamination from the dust (Figure 6.19; Figure 6.20). To ensure success in competitions, UWNRG maintains a backup plan. In the case of the upcoming competition, SAM is envisioned as the completion robot. However, the EMMA setup is kept as a backup, in case there is a last minute failure with SAM.

Figure 6.19: SAM setup in this form is provided to save the robotic playing field from dust. The figure shows the playing fields surrounded by four electromagnets (long metal rods with red and green wires).

Figure 6.20: Close-up of the area where the playing field from SAM setup will be placed. This area will be the one where the magnet and playing fields will be placed for the competition

6.1.6 Generic Processes, Challenges and Ambiguities

This study was conducted in university settings for an undergraduate group involved in creation of robotic setups for taking part in competitions. The ethnographic study highlighted various groups that were involved together to produce the final result of taking part (and at times winning) in competitions. The important idea during the ethnographic study was that the robot was a sociotechnical construct. Therefore, to understand the functioning of the robotic setup, the actual technical aspects have to be understood along with the social aspects that support the work domain. Currently, WIDF addresses the nuanced nature of activity through the hierarchy of acts that is developed in detail in the next chapter. Over the course of the study, two main interrelated themes were highlighted. First, robot design is a socially situated activity. Second, robot design is a collaborative activity. Both these insights point towards the socio-technical construction of the work domain.

6.1.7 Robot creation as a socially situated activity; ambiguities in UWNRG functioning

As it was shown in the study, the actual robot creation involved both the technical teams and support teams (marketing and business). While both the teams were involved in initial planning of the possible courses of action throughout the semester, the everyday activity made further lines of activity visible. Therefore, in the weekly meetings, the results of the various endeavors were evaluated to formulate further steps for the progress of the group towards their goals. During these meetings, the ambiguities and challenges were brought to light. The ambiguities that the individual team members faced were in regards to their tasks (described above in detail); further ambiguities were also present for the teams as a whole. Both these sources and challenges of ambiguities were discussed in the weekly meetings. Various team members shared their past experiences to nullify the sources of ambiguity with proper information. Therefore, there was a sharing of information that enabled the new members to learn from the older members and enabled the group to function effectively.

The ambiguities faced by the individual members as well as the overall group came from a variety of sources. The ambiguities faced by the technical teams came from the challenges brought about by the technical aspects of the robotic setups and also from the various laboratories in which the fabrication of playing fields was conducted. For example, the undergraduate members of UWNRG were to be supervised by laboratory assistants in the fabrication procedure and the handling of equipment. Therefore, sources of ambiguity included understanding the technical challenges as well as coordinating time schedules for appropriate progression of work. The ambiguities faced by the marketing and business groups involved in finding possible sources of funding, adopting persuasive means to gather funding and also proper usage of funds. The marketing teams were always on the lookout for new connections; therefore, the likelihood that a particular prospect would pay them adequate funds was rather ambiguous to begin with. However, through persuasive interchange and awareness of the situation, the possible ambiguities were removed to get an adequate outcome of the project and the necessary funding opportunities.

Further, the functioning of UWNRG showed how cognitive activity should be understood as a social construct. A cognitive view of the robotic setup building process would reveal the decisions and intellectual steps to be taken. However, the social milieu played a crucial role in the acquisition and management of funds which in turn shaped the technical choices of the robotic setup. For, example, the choice of materials for robotic setup construction along with the prices of the related equipment shaped the choice of the group in terms of which materials to invest in and which equipment would be monetarily feasible in the long-run. Thus, along with the technical project constraints, the social constraints had to be taken together for a unified understanding of the work domain.

6.1.8 Generic processes involved in robot design as a collaborative venture

The robotic setup design was a collaborative venture between the technical team and the non-technical robotic teams. This collaborative activity can be understood in terms of the generic processes available in this work domain. As a group, the UWNRG members were involved in recruiting members (process of recruitment). This recruitment involved advertising of positions, assessing of potential individuals, and rejecting of individuals that did not fit the expectations of the group as a whole.

Further, formation and maintenance of identity for the group was an ongoing process. The marketing team was involved in various events, where they promoted themselves and showcased UWNRG activities. This involved wearing t-shirts with the UWNRG logo that reinforced a common identity of the group and supported their ventures to establish a presence in the Waterloo community. A related notable aspect of this work domain was the processes involved in building capabilities of funds. Thus, in terms of the process of funding, three subprocesses were involved. The first subprocess was the identification of the patrons; next, the process of achieving reciprocity with the patrons. Finally, there was the process of managing funding for the advancement of the group as a whole.

Along with the above, the individual members involved in various tasks related to the robots were developing stockpiles of knowledge (both technical and social). Further, the individual team members were also charged with the group to develop the overall knowledge of the group. For example, the business group involved in the funding of the projects identified particular patrons who were ready to support particular types of equipment (funding in cash or kind). The technical teams were also made aware of this knowledge. Therefore, the technical teams could formulate their activities in terms of the likelihood of the anticipated fund capabilities of the entire group. The stockpiles of knowledge also support career progression of the members. The members who have worked hard to understand and develop robots are promoted to team leaders to further the research and development of individual groups. These above generic processes in maintaining the social ecology of UWNRG have a direct impact on the technical design. The technical design is shaped by the availability of funding and possible sources of ambiguities and challenges. The UWNRG group was involved in formulating activities and nullifying sources of ambiguities to accomplish their goals. Overall, the UWNRG functioning involved a consideration of both the social and the technical dimensions of activity. These dimensions could be characterized as generic processes existing in the socio-technical ecology.

6.1.9 Conclusion

The emphasis on robotics in Site 2 provided an insight into how robotics at a small-scale hold implications for HFE research in the area of human robot interaction. Making a robot, as the workings of Site 2 demonstrate, is not only a technical process but requires a sociotechnical understanding. The choice of the robot and its end design is severely constrained by the budget and human labor. As a result, studying the robotic design and development process involves considerations related to the recruitment of right pair of hands, acquiring and managing patronage, as well as successful team functioning in order to win competitions. In short, in Site 2 the robot is understood as an ecological component. Even though many aspects of the Site 2 appear quite idiosyncratic, this site also presents generic aspects of integration of cost and design encapsulated by the overarching social ecology for successful engineering outcomes. In general, Site 2 demonstrates that robotics at the small scale has implications for human robot interaction, and specifically present considerable opportunities for interface design for this venture. Currently, the socially situated nature of the work domain is well captured by WIDF in terms of the hierarchies of the person and acts (discussed in the next chapter). In the next chapter the engineering models (CWA and its extension) pertaining to small-scale robotics are addressed in greater detail.

Chapter 7: Site 2—Engineering analysis for Robotics

7.1 Introduction

In Chapter 6, an ethnographic study of the undergraduate nanorobotics group (i.e., UWNRG) of the University of Waterloo was presented. In this study, it was highlighted that UWNRG functioned as an autonomous undergraduate research group whose main aim was to win robotic competitions. In order to support this main aim, the groups acquired resources and funds; managed resources as well as themselves; along with, maintaining a public presence in Waterloo. In this current chapter, the main aim is to present the analysis for gleaning design requirements from this work domain. The analysis will be presented for CWA and WIDF; later they will be compared to each other. In developing the CWA approach, three major texts (Vicente, 1999; Bisantz & Burns, 2009; Burns & Hajdukiewicz, 2004) and two documents (Kilgore, St-Cyr & Jamieson, 2009; Miller & Vicente, 2001) were used as foundations for developing the CWA based analysis. Due to the structure of the RC-hierarchies, the number of requirements gleaned by WIDF is greater than that of CWA.

7.2 CWA

7.2.1 System formulation

In the present work domain, UWNRG functioned as a tightly-knit conglomeration of the different technical teams (for e.g., MAYA, EMMA, PAMELA, among others), the control team; the business and marketing teams. These various teams present both social and technical constraints. Since CWA treats the social and technical constraints differently, they are modeled separately as different sets of constraints. Therefore, the work domain consists of two subsystems – technical and social. The technical subsystems consists of the control team as well as the individual technical teams; whereas, the social subsystems consist of the business and marketing teams. These distinctions for the system formulation were used as a basis for developing the WDA.

7.2.2 WDA

The first step in creating the WDA is the AH (AH 1.0, Figure 7.1). In the AH, the system is partitioned in terms of two halves reflecting the social and technical dimensions. The first level of functional purpose consists of four main purposes. The first two correspond to the technical aspects, such as, winning competitions and making robots, playing fields and control systems. The next two entities at this level of functional purpose are social in nature; they include obtaining and managing funding and maintaining a presence in University of Waterloo community.

At the next level of abstract functions, the technical aspects include three entities. First, the fabrication of the playing fields involves conservation of mass based on stoichiometric relations. Next, for individual projects, there are other fundamental principles and processes involved. For example, the team PAMELA uses principles of fluid dynamics in the formulation of the robot. Whereas, other teams such as MAYA uses principles and laws related to the superconductivity for the formulation of their robots. Along with the fundamentals required for formulating the robots and playing fields, the laws of magnetism are required for the functioning of the control system for controlling the robot movement in the playing field. Along with these technical constraints, the social aspect at the level of abstract functions involves the balance of power along with the balance and flow of priorities. The balance and flow of economic values and priorities are related to the sustainability of UWNRG as a whole. Therefore, the economic considerations are modeled as values and priorities that are needed to enable the functioning of the group monetarily as well as managing the flow of resources among various projects. Further, the balance of power is present among the various members of the team in a manner so as to ensure effective team functioning. As described in chapter 6, the structure of UWNRG is hierarchical yet flat; i.e., the everyday working is very democratic. There is a need to account for the balance of power for the team functioning.

At the third level of generalized function, the technical aspects consist of two major sets of processes. The first involves the robot and playing field fabrication processes; while, the second takes into account control processes required for controlling the robot.

In terms of the social aspects there are management and organizational processes for everyday functioning of the teams, as well as UWNRG as a whole. Further, there are processes related to the acquisition and management of resources for devising the robots, entering competitions, along with other overhead expenditures.

At the level of physical function, the technical aspects consist of the robots, robot playing field, software control setup, and electromagnetic/magnetic actuators. These various entities together comprise of the entire robotic setup for the competition (i.e., currently being used for the entries to the robotic competitions). Alongside the technical aspects, there are social aspects related to the roles that the members occupy in UWNRG. For example, as described in chapter 6, many members occupy more than one role; i.e., they may be in a technical team as well as in the business team. Therefore, at this level of physical function, the function that the particular role provides in the overall functioning of the team is taken into account. Along with the roles of the team members, at this level, there is a necessity to account for the various ranks for the patrons who provide resources (in cash or kind). Currently, UWNRG uses three levels to categorize their patrons, based on the funding they provide (gold level, silver, etc.). These levels provide the function of supporting the UWNRG group as a whole.

Finally, at the level of physical form, the technical aspects of the domain can be described in terms of the ferromagnetic materials for the robot. An etched silicon wafer serves as the playing field; the software language python is used for the programming the control algorithm. Further, magnetic actuators used in the robotic setup have fine control of movement (often in the order of 13-1500 nm and speed of up to 1m/s). In terms of the social aspects, the conditions of the UWNRG members are accounted for at this level. Further, at this level the funds are also accounted for in terms of cash and kind that patrons provide to UWNRG.

Along with the above formulation of the AH, a causal representation is also presented (AH 1.1, Figure 7.3). In this formulation two main levels of abstract function and generalized function are developed in detail. In the technical aspects related to the abstract function level, the conservation of mass based on stoichiometric relations is present. There the initial mass of materials is transformed into the final mass by chemical reactions following stoichiometric relations. Further, the robot movement is possible due tot the laws of magnetism. In this situation the total energy of the robot (ferromagnetic materials) and the magnetic field is a conserved quantity. The initial energy of the magnet is potential energy, which changes to kinetic energy during the robot movement and returns to potential energy when the robot comes to a stand still. Along with the above technical aspects of the abstract function, the individual projects have their own principles for movement of the robot. For example, the project PAMELA involves the laws of fluid dynamics; whereas, the project MAYA involves the principles related to superconductivity. In the social aspects of the abstract function, there is an interaction between the entities related to the balance and flow of economic values and priorities.

At the level of generalized function, two main sets of processes are involved for the technical aspects of the work domain. In terms of the robot playing field, the silicon wafer undergoes etching to produce the etched silicon wafer and waste materials. Further, in terms of the robotic control processes. For the first phase of the competition, there is automated control in which the robot moves autonomously due to the preprogrammed control algorithm. In the second step of the competition, the control of the robot is manual and is done by one member of the team. Along with the technical aspects, in terms of the social aspects, two main sets of the processes exist. First, involves the management/organizational processes related to the group. This set of processes includes recruitment of members; development and communication of knowledge for the group; as well as processes required for maintaining the group's cohesiveness. A second set of processes involves resource management. These processes include acquiring resources, managing resources and maintaining reciprocity with patrons, which enable the group to acquire further resources.

Along with the above two representations, the third representation consists of an abstraction-decomposition space (WDA 1.0, Figure 7.3). In this space, in terms of the decomposition, the system is divided into a system and subsystem. The sub system is divided in terms of two sub systems – technical and social. The technical subsystem consists of individual technical teams and the control team, while the social subsystem consists of the business and marketing teams. At the systemic level, the functional purpose consists of winning the competitions. While at the subsystem levels, the teams have different purposes. For example, the individual technical teams are involved in the making of the robots and the playing fields, while the control team is involved with the control system setup. In contrast to the technical teams, the business and marketing teams are involved in maintaining presence in the UW community as well as involved in resource management. Similar to the distinctions at the level of functional purpose for system and subsystem, similar distinctions are also made for the other levels of abstraction. These categorizations are developed in grater detail for all levels of abstraction and the different systems and subsystems. These are depicted in detail in WDA 1.0.

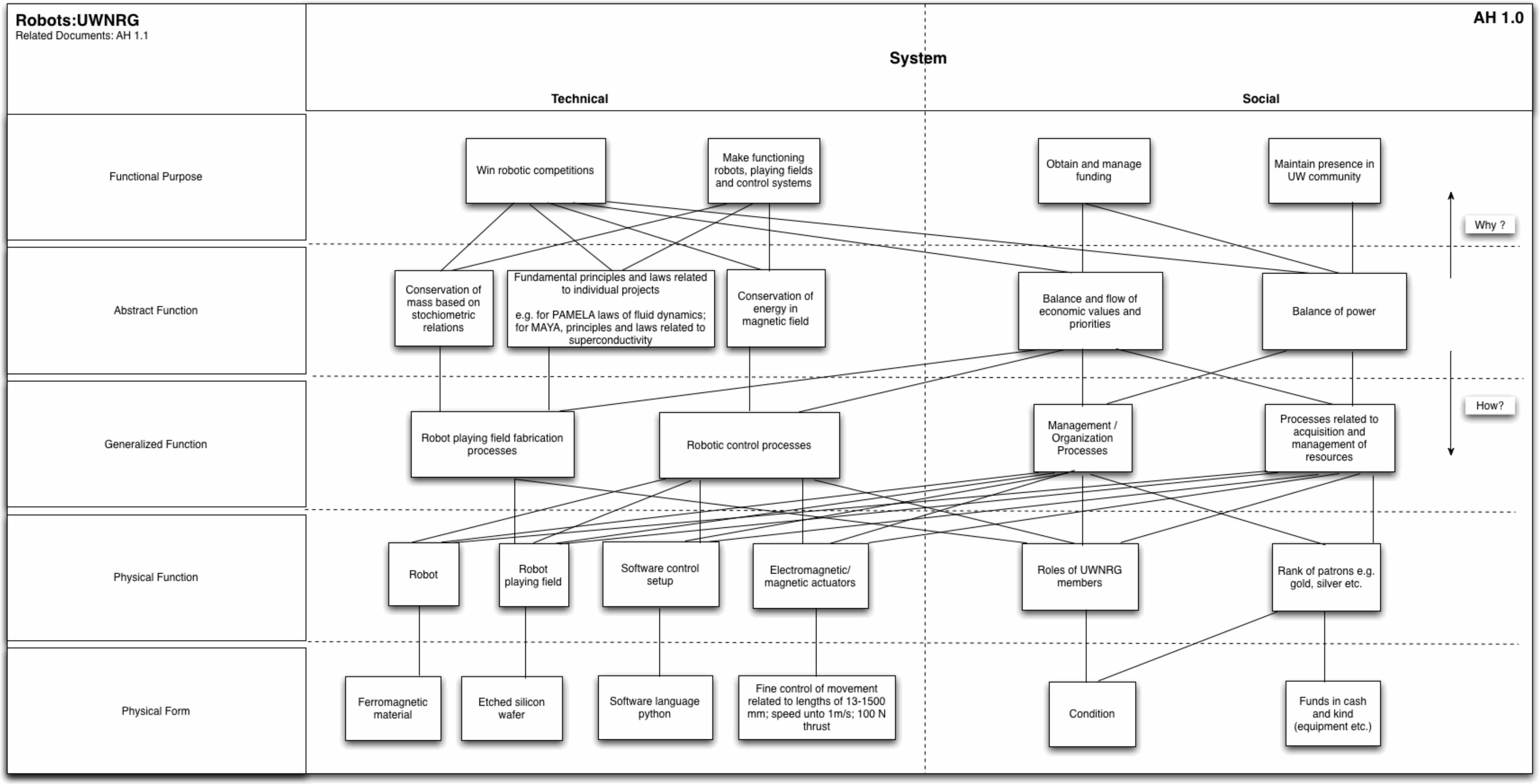


Figure 7.1: AH for UWNRG

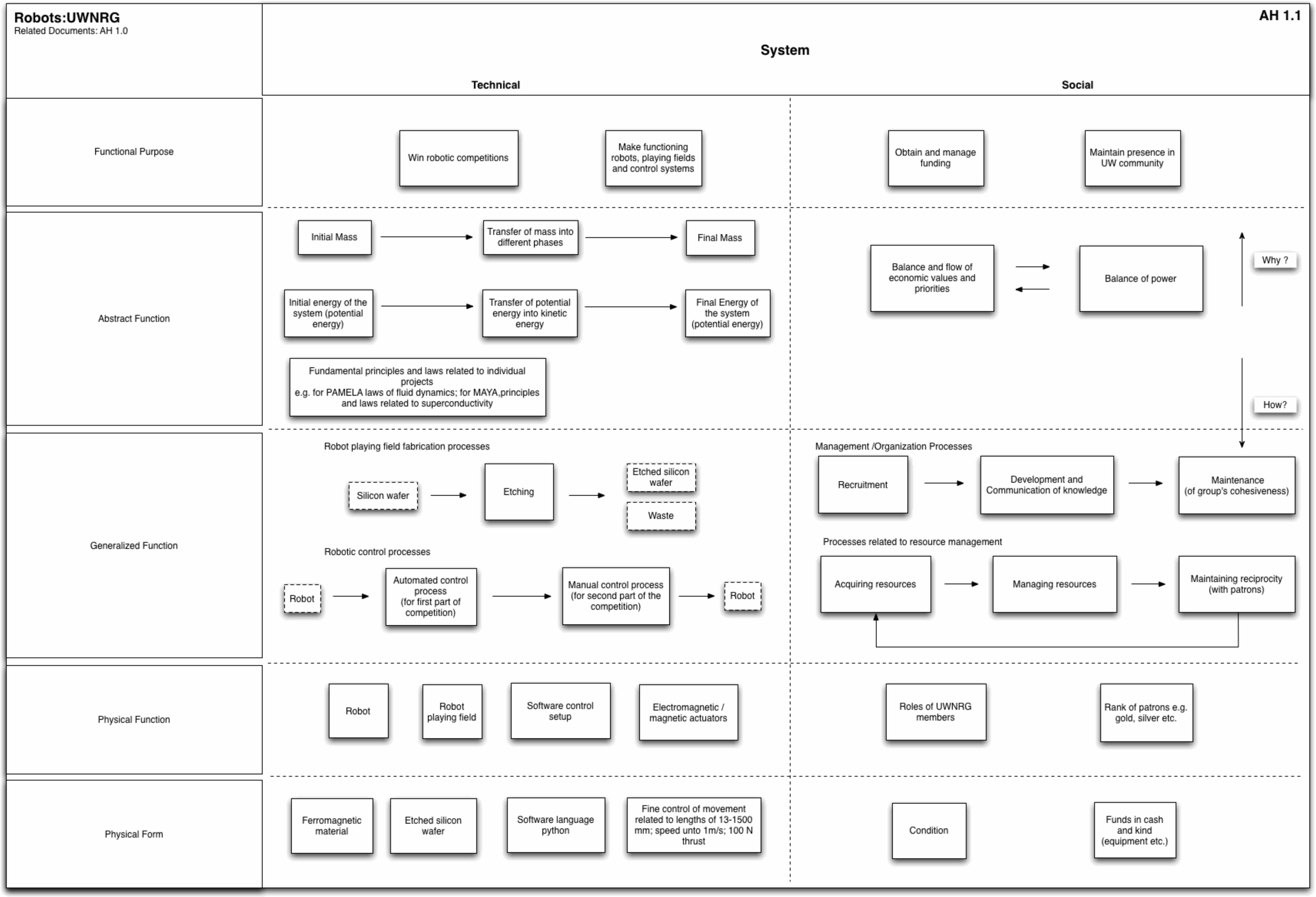


Figure 7.2: Causal representation for AH for UWNRG

WDA 1.0

Robots:UWNRG Related Documents: AH 1.0	**System**	**Sub-System**		
		Technical subsystem		**Social subsystem**
		Individual Teams (e.g. EMMA, MAYA, SAM, among others)	**Control Team**	**Business & Marketing Team**
Functional Purpose	Win robotic competitions	Make functioning robots and playing fields	Make functioning control systems	Maintain presence in UW community Obtain and manage funding
Abstract Function		Conservation of mass based on stochiometric relations Fundamental principles and laws related to individual projects. e.g. for PAMELA laws of fluid dynamics; for MAYA,principles and laws related to superconductivity	Conservation of energy in magnetic field	Balance and flow of economic values and priorities Balance of power
Generalized Function		Robot and Playing field fabrication processes Maintenance (of group's cohesiveness) Managing resources	Automated control process (for first part of competition) Manual control process (for second part of the competition) Maintenance (of group's cohesiveness) Managing resources	Recruitment Development and Communication of knowledge Maintenance (of group's cohesiveness) Acquiring resources Managing resources Maintaining reciprocity (with patrons)
Physical Function		Robot Robot playing field	Software control setup Electromagnetic/ magnetic actuators	Roles of UWNRG members Rank of patrons e.g. gold, silver etc.
Physical Form		Ferromagnetic material Etched silicon wafer	Software language python Fine control of movement related to lengths of 13-1500 mm; speed unto 1m/s; 100 N thrust	Condition Funds in cash and kind (equipment etc.)

Figure 7.3: WDA for UWNRG

7.2.3 ConTA

The second step of the CWA consists of the Control task analysis. In this step three major control tasks were identified. The first task consists of the making the robotic setup for the competition (ConTA 1.0, Figure 7.4). The second step consists of integrating the hardware to the software for the control systems design (ConTA 2.0, Figure 7.5). Finally, the third control task consists of getting funds and maintaining reciprocity with the patrons (ConTA 3.0, Figure 7.6). Apart from these three control tasks, another control task that is prominent in the present context is that of the maintenance of team functioning as a whole. Since this task wasn't developed in detail in the Chapter 6, it has not been developed any further in this section.

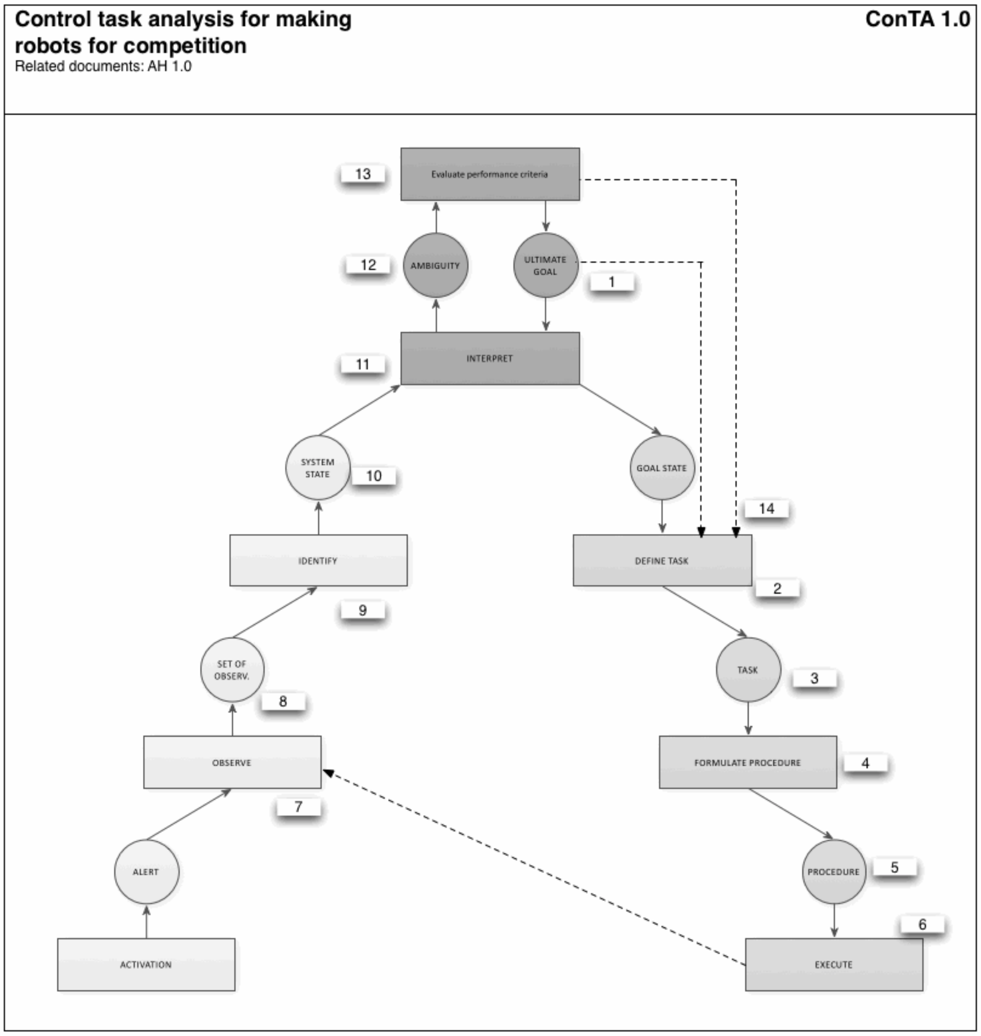


Figure 7.4: Control Task Analysis for making the robotic setup

Control task analysis of making robots for the competition -Decision Ladder **ConTA 1.0**
Related documents: AH 1.0

No.	Ladder Code	Notes	Type	Abstraction Level
1	Ultimate goal state	Identify the goal state of winning in the competition (typically the microrobot challenge in the IEEE International Competition on Robotics and Automation, ICRA)	Knowledge State	Functional Purpose
2	Define task	The task of selecting the possible robot for the competition, based on the various robotic projects underway, is defined	Information Processing Activity	Generalized Function, Physical Function, Physical Form
3	Task	A task state is formulated, based on the robot competition date, competition guidelines, possible funding, among other considerations.	Knowledge State	Generalized Function, Physical Function, Physical Form
4	Formulate procedures	Plan sequence of actions for the various members depending on the tasks of the robotic control setup for the controls team; the robot and robotic field related tasks for the technical team members; and obtaining funding for marketing and business teams	Information Processing Activity	Physical Function, Physical Form
5	Procedure	The procedures are formulated into a procedural state based on the different teams and the division of labor for each team.	Knowledge State	Physical Function, Physical Form
6	Execute	The division of labor, encapsulated in the procedural state, is executed by the various teams at a localized level.	Information Processing Activity	Physical Function, Physical Form

7	Observe	Based on the execution of various tasks, observe the information and data from the respective tasks on a weekly basis.	Information Processing Activity	Physical Form, Physical Function
8	Set of Observations	Formulate a set of observations about the nature of the tasks undertaken by each team and the overall state of UWNRG	Knowledge State	Physical Function, Generalized Function
9	Identify	Identify the system state on the set of observation. Therefore, for each team, tasks are taken together along with constraints. Further, relation of the tasks are understood in terms of the overall UWNRG functioning, appraised on a weekly and monthly basis.	Information Processing Activity	Physical Function, Generalized Function
10	System state	Based on the identification of the state of UWNRG, as a whole, a system state is formulated	Knowledge State	Physical Form, Physical Function, Generalized Function, Abstract Function
11	Interpret	The various tasks undertaken by the different teams and their states are interpreted in terms of future consequences	Information Processing Activity	Functional Purpose, Abstract Function, Generalized Function
12	Ambiguity	If there is ambiguity in the tasks or the possible consequences of the tasks then the possible criteria are evaluated	Knowledge State	Functional Purpose, Abstract Function, Generalized Function
13	Evaluate	Evaluation of criteria is done to situate the present state of the system in terms of the constraints of the robotic competition, as well as that of the resources. For example, in case of robot design and fabrication, the members	Information Processing Activity	Functional Purpose, Abstract Function

		have to rethink their ways of achieving the outcome		
14	Define Tasks	Based on the evaluation of the performance criteria and state of the system, a set of operational tasks is defined to reach the outcome. In this case tasks are defined, in order to ensure the proper functioning of UWNRG and also to ensure that the robots are made on time to enter the competition. The rest of the procedures, formulate procedures and execution of tasks are similar to the previous states from 3-5 listed above and are not developed any further.	Information Processing Activity	Generalized Function, Physical Function, Physical Form

Table 7.1: Details of Control task analysis for making the robots

Control task analysis for integrating hardware to software for the control system **ConTA 2.0**

Related documents: AH 1.0

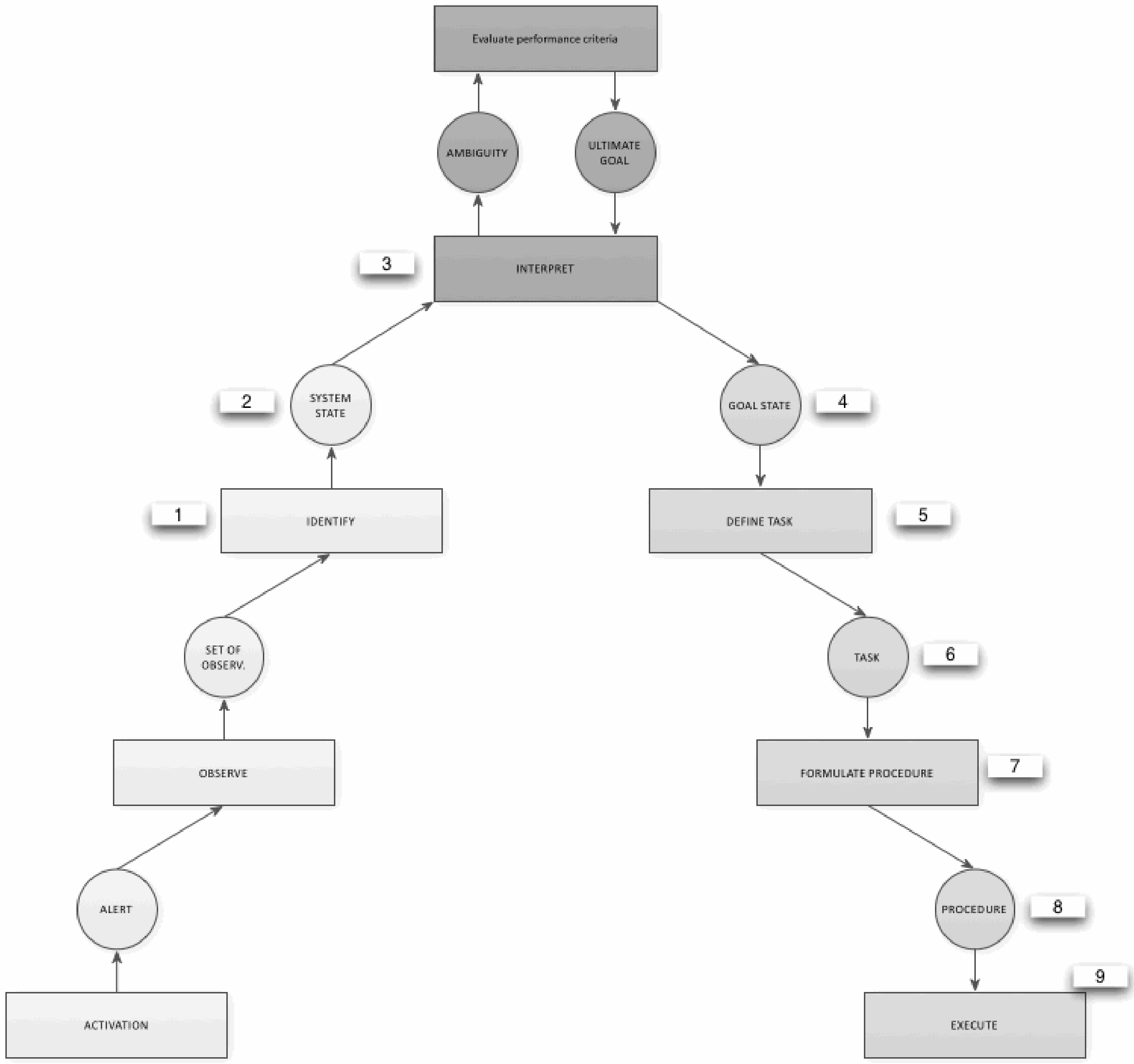


Figure 7.5: Control task analysis for integrating hardware and software

Control task analysis of integrating hardware and software for the control system setup-Decision Ladder Related documents: AH 1.0				**ConTA 2.0**
No.	**Ladder Code**	**Notes**	**Type**	**Abstraction Level**
1	Identify	The state of the system is identified in terms of the existing hardware, devised control algorithm, and the competition requirements	Information Processing Activity	Physical Function, Generalized Function
2	System state	Based on the above processing activity of identification, a system state is devised to comprehend the overall state of UWNRG and the possibilities of further activity	Knowledge State	Physical Form, Physical Function, Generalized Function, Abstract Function
3	Interpret	The system state is interpreted in light of the overall goals, task of integration, and time available for the competition	Information Processing Activity	Functional Purpose, Abstract Function, Generalized Function
4	Goal state	An interim goal state is formed, based on the interpretation of the various constraints, such as hardware, software and time constraints	Knowledge State	Generalized Function, Physical Function
5	Define Task	The task of integration is described in terms of three main aspects related to the hardware, software and the fine-tuning of the software algorithm (after integration with the hardware). The fine-tuning is portrayed as a separate component because the fine-tuning of the algorithm is crucial for reducing the amount of time taken to complete the first challenge of the competition.	Information Processing Activity	Generalized Function, Physical Function, Physical Form

		This task involves considerable amount of time and is treated separately.		
6	Task	The above three components are encapsulated into a task state to identify how they can be together fit along each other as a coherent whole, for the task state	Knowledge State	Generalized Function, Physical Function, Physical Form
7	Formulate Procedure	Based on the tasks, formulate a detailed procedure to plan the sequence of actions for integrating the hardware and the software. This procedure also includes refining of the control software parameters, for seamless autonomous control in the first part of the component; as well as, manual control for the second half of the competition.	Information Processing Activity	Physical Function, Physical Form
8	Procedure	The procedures are together combined to form a procedure state. This state encapsulates all the information processing activities of the previous information processing activity.	Knowledge State	Physical Function, Physical Form
9	Execute	The procedures formulated above executed thus enabling manipulations to link the hardware to the software and fine tune it for the competition	Information Processing Activity	Physical Function, Physical Form

Table 7.2: Details of Control task analysis for integration of hardware and software

Control task analysis for getting funds and maintaining reciprocity with patrons Related documents: AH 1.0				**ConTA 3.0**
No.	**Ladder Code**	**Notes**	**Type**	**Abstraction Level**
1	Activation	In weekly meetings detect the need for funding in cash or kind	Information Processing Activity	Physical Form
2	Alert	Form an alert state about the need for funding and possibilities of further action on behalf of business team	Knowledge State	Physical Form, Physical Function
3	Observation	Identify the information about how much funding is required in cash or kind	Information Processing Activity	Physical Form, Physical Function
4	Set of observations	Formulate a set of observations in terms of the required funding and the teams that require the funding	Knowledge State	Physical Function, Generalized Function
5	Identify	Identify the present state of UWNRG in terms of funding and interaction with clients	Information Processing Activity	Physical Function, Generalized Function
6	System State	Formulate the system state in terms of the past funding, available funds, past patrons and possible new patrons currently being contacted.	Knowledge State	Physical Form, Physical Function, Generalized Function, Abstract Function
7	Interpret	Interpret the consequences for asking for funds from various patrons . For e.g. a sponsor does not fund any disposable equipment or materials. Therefore, to obtain funding from that patron for chemicals (disposable materials), the Business team members have to provide a reasoned argument to show that chemicals are required to fabricate the robotic fields. Alternatively, the funding for chemicals could be presented to different patrons or could be	Information Processing Activity	Functional Purpose, Abstract Function, Generalized Function

		procured with existing funds.		
8a	Ambiguity	If there is ambiguity in the possibilities and sources of funding, different alternatives are sought to determine which goal state would be feasible depending on the system state	Knowledge State	Functional Purpose, Abstract Function, Generalized Function
9a	Evaluate	Evaluate the goal and the possible sources of actions for funding together based on required funds, past experience with funding agencies and possibilities of new agencies.	Information Processing Activity	Functional Purpose, Abstract Function
10a	Ultimate goal state	Formulate an ultimate goal state by the evaluation of alternatives interpreting the state of the system and consequences and removing ambiguity in the situation	Knowledge State	Functional Purpose
8	Goal State	Formulate a goal state based on the interpretation of the system state, possibilities of funding and the patrons involved in the funding	Knowledge State	Generalized Function, Physical Function
9	Define Task	Based on the goal state, the task of obtaining funding is defined, i.e., the amount of money to be requested to the various patrons is defined. The members who would approach these patrons are also defined	Information Processing Activity	Generalized Function, Physical Function, Physical Form
10	Task	Overall state of the task is formulated in terms of the division of labor between the members of the business team based on the tasks and the possible sources of funding	Knowledge State	Generalized Function, Physical Function, Physical Form
11	Formulate Procedure	Based on the task and the division of labor, the detailed procedures are formulated for the sequence of steps regarding obtaining funding	Information Processing Activity	Physical Function, Physical Form
12	Procedure	Based on the formulation of a procedural state regarding the search for funding and the steps	Knowledge State	Physical Function, Physical Form

		to receive it is formulated		
13	Execute	The formulated manipulations are executed to obtain funding	Information Processing Activity	Physical Function, Physical Form
14	Identify	After receiving the funding from the patron, identify the system state after receiving the funding from the patron	Information Processing Activity	Physical Function, Generalized Function
15	Task	Based on the identification of the system state and the funding received, the task of maintaining reciprocity with the patrons is defined	Knowledge State	Generalized Function, Physical Function, Physical Form
16	Formulate Procedure	Plan sequence of actions based on how to thank the patron. For example, by sending a plaque to acknowledge the support as well as advertising on social media	Information Processing Activity	Physical Function, Physical Form
17	Procedure	Procedures for maintaining reciprocity with the patrons are finalized	Knowledge State	Physical Function, Physical Form
18	Execute	Execute the formulated procedures for sending gifts, highlighting name of patrons in social media, among other actions to support patrons and maintain reciprocity	Information Processing Activity	Physical Function, Physical Form

Table 7.3: Details of control task for getting funding and managing reciprocity

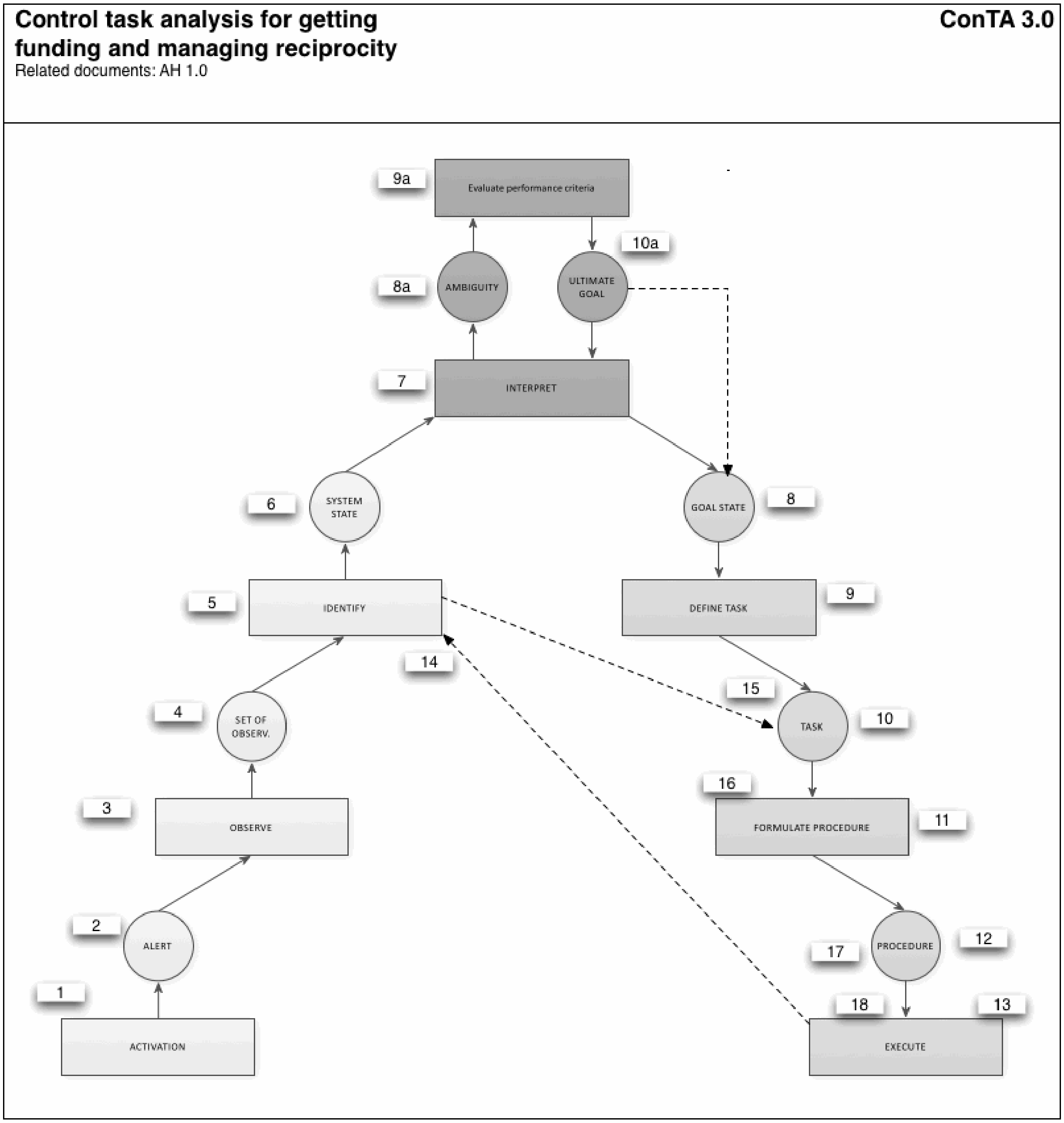


Figure 7.6: Control task for getting funding and managing reciprocity

7.2.4 StrA

In terms of strategies, individual teams (both technical and non-technical) have their multiple strategies in terms of conducting their activities. Some of them include strategies for getting access to equipment, strategies for attracting and retaining labor, strategies for integrating control systems, among others. In this section, two main strategies are developed in greater detail. The first involves the technical team and the manner in which they achieve access to the chemicals. As it was earlier mentioned in chapter 6, the funding for perishable products and materials such as chemicals is difficult to obtain. Therefore, the various strategies for obtaining chemicals were developed in greater detail (Str 1.0; Figure 7.7). Apart from the first set of strategies involving technical teams, the second set of strategies involves strategies employed by the business and marketing team for obtaining funding from the patrons (Str 2.0; Figure 7.8).

Strategies analysis for getting access to chemicals	**StrA 1.0**
Related documents: AH 1.0	
1	In the first strategy, the aim is to obtain funding in cash. Since the mobility of cash is possible, the UWNRG members often divert some cash obtained for other products towards purchasing chemicals. The chemical purchases are typically made at the chemistry stores at UW.
2	The second strategy for obtaining chemicals is employed when the chemicals required for the individual projects are of lesser quantity and the work on the projects are at a preliminary stage of experimentation, often involving many different ideas and ways to fabricate the robots. In this case, the team members who conduct fabrication in particular laboratories ask for the use of chemicals. Due to the small amount of chemicals used, UWNRG members often get the chemicals for free. In case of expensive chemicals, UWNRG takes into account some mechanisms for paying the price of the chemicals, to the lab. Thus, getting access to chemicals.
3	The third strategy consists of getting chemicals to be funded by the patrons. As described before, not all funding agencies provide money for perishable products and materials. The use of chemicals has to be highlighted in terms of the robot design process. Thus, establishing the value of the perishables product in terms of the final non-perishable product. Therefore, obtaining funding from patrons for buying chemicals

Table 7.4: Details of strategies for getting access to chemicals

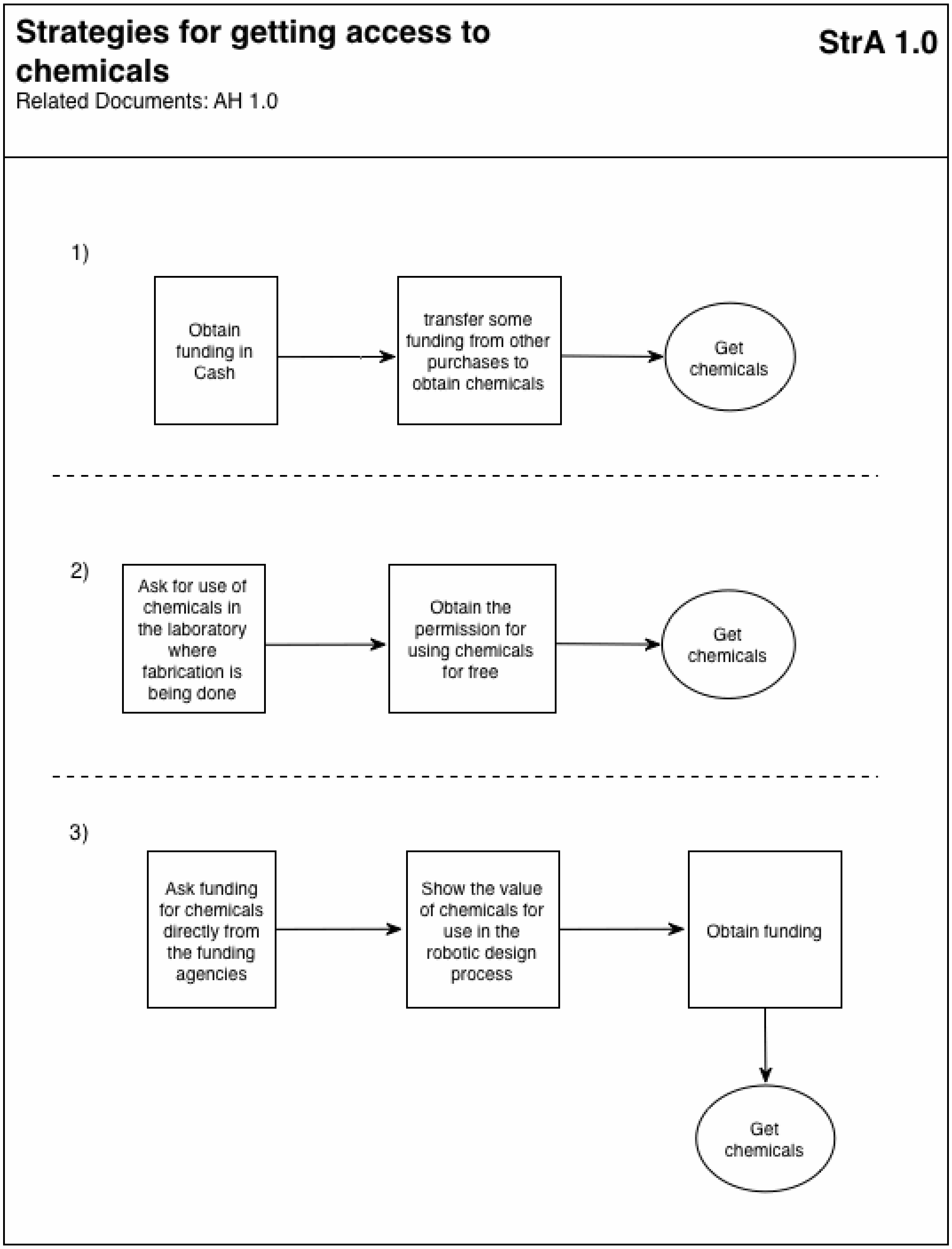


Figure 7.7: Strategies for getting access to chemicals

Strategies analysis for getting funded by patrons **StrA 2.0** Related documents: AH 1.0	
1	The first strategy involves contacting patrons directly and requesting for funding in cash. In the process, the business team provides a presentation about UWNRG and its goals. By persuasive arguments, the business team receives funding
2	The second strategy for getting support, involves contacting patrons and requesting them for particular equipment or software. In the process, the business team provides a presentation to convince the patrons to provide funding. If successful, the patron provides the funding in terms of equipment or software.
3	The third strategy for funding involves getting renewed support from patrons who have provided funds in the past. In order to get refunded in the future, the marketing team highlights the patrons by providing coverage in social media. Further, after winning competitions, the sponsors are highlighted in interviews and websites. Further, the marketing and business teams follow up with the patrons and send them gifts to show gratitude for the support they have provided in the past. This enables the channels of support to remain open for future cases and aids in UWNRG to get funding.

Table 7.5: Details of strategies for getting funded by patrons

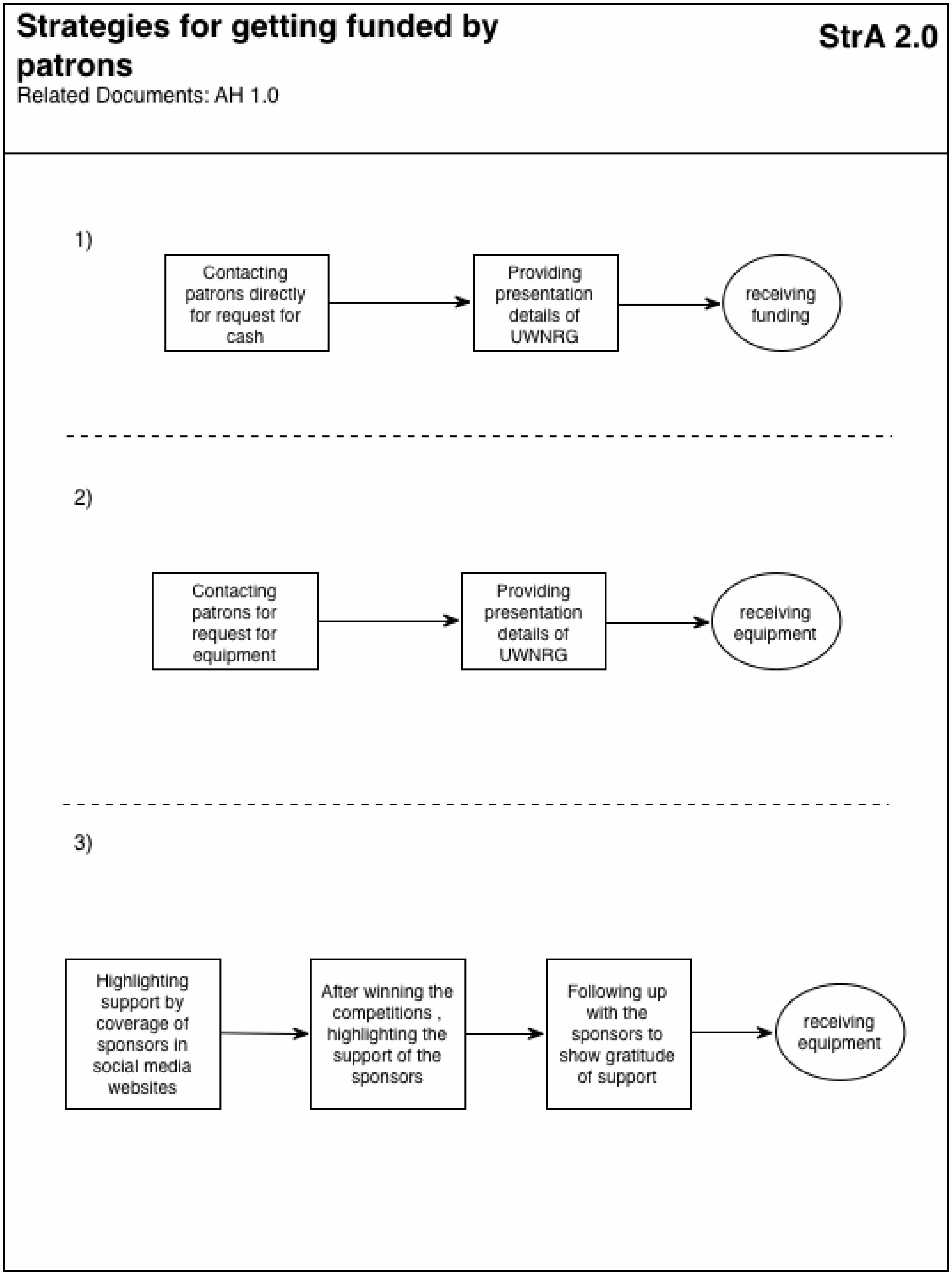


Figure 7.8: Strategies for getting funded by patrons

7.2.5 WCA

Finally, in the last step of the CWA, the worker competencies are discussed in greater detail. Three lists of worker competencies are provided corresponding to the three main control tasks present in the work domain. Thus, WCA 1.0 (Table 7.6) refers to the SRK analysis for making the robotic setup. WCA 2.0 (Table 7.7) refers to the SRK analysis for integrating the hardware to the software. WCA 3.0 (Table 7.8) refers to the SRK for getting funds and managing reciprocity with the patrons.

Worker Competencies Analysis for the making the robot **WCA 1.0**
Related documents: AH 1.0, DL 1.0

Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge-Based Behavior**
Associated Number	**Associated Number**			
Ultimate Goal / Task	Define Task		Rules about the competition (for e.g. robot and robot playing field, dimensions etc.). Heuristics gained from past experience about schedules for preparing for the competition	Knowledge about nanotechnology fabrication, knowledge about robotics
1,3	2			

Formulate Procedures	Procedures	Planning skills required for allocating tasks among members. Phased planning for steps involving robot making, fund gathering, fund management, competition arrangement, among other phases	Heuristics based on past experience about rough time schedules for the phases to begin and end during academic years	
4	5			
Execute		Dexterity required for fabrication. Presentation skills required for presenting proposals to members of UW community for access to labs and resources		
6				
Observations	Set of Observations	Skills required to gauge the situation and ascertain whether the project is running correctly according to the need, and on time (both on a weekly basis and monthly basis)	Heuristics based on experience about rough time schedules based on previous competitions	
7	8			
Identify	System State	Skills required to gauge whether UWNRG is functioning properly as a group. For e.g. whether the presence of the group is maintained during the weekly meetings, are members doing their work, among other aspects.		Knowledge about project requirements and the whole UWNRG group

9	10			
Interpret, Evaluate	Ambiguity	Skills required to detect flawed situations in regard to UWNRG functioning. For e.g. the members not working or producing the outcomes on time, resulting in project slippages	Heuristics based on past experience for understanding ambiguous situations and possible courses of action to keep the robot creation process on schedule	
11,13	12			
Define Task		Management and planning skills required to reformulate the tasks and plan the situation accordingly. For example, if an equipment is unavailable, then the first step is to search for the equipment, if it its not possible to receive the equipment then new research direction is sought and associated tasks reformulated		Knowledge about the UWNRG group as a whole required to understanding the delegation of tasks and task sub-components.
14				

Table 7.6: Worker competencies analysis for making the robot

Worker Competencies Analysis **WCA 2.0**
SRK for integrating hardware and software for the control system setup
Related documents: AH 1.0, DL 2.0

Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge- Based Behavior**
Associated Number	**Associated Number**			
Identify	System state			Knowledge of hardware circuits and software language, Python
1	2			
Interpret	Goal State	Perceptual skills/ decision making skills required for detecting problem areas related to the integration of the hardware and software	Heuristics based on past experience about finding possible problems	Knowledge of hardware circuits and software language, Python
3	4			
Define Task	Task	Planning skills required for planning various phases of the tasks of integration	Heuristics based on past experience of the various tasks, allow for providing proper phased approach to control systems integration for the competition	
5	6			

Formulate procedure	Procedure	Planning skills required for allocating resources to each tasks related to the hardware and software setup	Heuristics based on past experience about the members and their motivation and capability. These heuristics are is helpful for allocating the tasks	Knowledge required about the time taken for team members working on the tasks
7	8			
Execute		Dexterity and electronic skills required for setting up control circuit. Programming skills required for coding the algorithm.		
9				

Table 7.7: Worker competency analysis for integrating hardware and software for the control system

Worker Competencies Analysis **SRK for getting funding and managing reciprocity** Related documents: AH 1.0, DL 3.0				**WCA 3.0**
Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge-Based Behavior**
Associated Number	**Associated Number**			

Activation	Alert		Heuristics developed with past experience help with funding. For e.g. there is necessity to enquire whether funding is required at any given point of the project development	Knowledge about funding schedules of agencies such as engineering society (EngSoc) that provides funding on a term-to-term basis
1	2			
Observation	Set of observations	Based on discussion and possible sources of funding, the possibilities of obtaining funding in terms of cash or kind	Heuristics based on past experience about possible good sources to support certain kinds of equipment/ software	
3	4			
Identify	System state	Skills required for gauging the need for funds at the level of individual teams, as well as the overall UWNRG.	Heuristics based on past experience about possibilities of funding from certain patrons depending on the amount of funds and the kind of research funding required	Knowledge is required about the funding capabilities of patrons that have supported UWNRG in the past
5	6			

Interpret	Ambiguity	Skills required for interpreting the current state of funding. Also for discovering and removing ambiguities to form a concrete goal state related to the goals to be accomplished in the short run (weekly) as well as in the long run (monthly), for the competition. Ambiguities may be present due to the unclear reply, or lack of reply from patrons regarding funding; certain policies that may curtail funding for a few materials; among others.		
7	8a			
Evaluate	Ultimate Goal, Goal state	Evaluation of these ambiguities and their removal are done in light of the ultimate goal state of winning the completion. Thus, decision making and planning skills (short terms as well as long term) are paramount at this stage		Knowledge about past patrons and possibilities of future patrons
9a	10a, 8			
Define Task	Task	Planning skills for defining tasks and the manner in which funding agencies are to be approached		
9	10			
Formulate Procedures, Execute	Procedure	Planning and social skills are required for contacting the various patrons and presenting funding proposals.		
11, 13	12			

Identify, Formulate Procedure, Execute	Task, Procedure	Interpersonal skills required for formulating the appropriate means of maintaining reciprocity with the patrons. Steps 16- 17 have similar skills depicted in 11-13 above and are not discussed in detail.	Rules for social interchange, heuristics for professional conduct.	Knowledge about the past projects in which the patron has provided support as well as knowledge of the UWNRG reciprocity towards them.
14, 16, 18	15, 17			

Table 7.8: Worked competency analysis for acquiring funding and managing

7.3 WIDF

After discussing the CWA models, I turn towards the models presented by WIDF. As described before, the WIDF analysis consists of three RC hierarchies pertaining to the environment, agent and acts. These three hierarchies are explained below in greater detail. The first step in the WIDF analysis begins with the system formulation.

7.3.1 System Formulation

In contrast to CWA, the formulation of sociotechnical in WIDF is presented as a hybrid. In other words, sociotechnical components are equally technical and social. Therefore, in the formulation of the system, distinctions between the social constraints and technical aspects of the domain are not specifically created, as it was in the case of CWA.

7.3.2 RCH Environment

In considering the WIDF analysis, I begin with the RCH for environment (RCH 1.1, Figure 7.9). In the first layer of functional purpose, there are four intertwined purposes. These include winning robotic competitions; making functioning robots, playing fields, and control systems; obtaining and managing funding; as well as maintaining presence in the UW community. At the next level of abstract function, five entities are highlighted. This level includes conservation of mass based on stoichiometric relations for fabricating playing fields (on some cases, the robots). Further, many technical teams have fundamental principles and laws related to the individual projects; for e.g., the project PAMELA includes laws of fluid dynamics, whereas, MAYA includes principles of superconductivity. Along with considering fundamental principles related to robots, the control team takes into account the principles of energy in magnetic field. For the present robotic setup, the magnetic field is a crucial aspect of the design of the control system. Along with the laws of physics, for the proper functioning of the work domain, there is a necessity for understanding the balance and flow of economic values and priorities as well as balance of power in UWNRG as a whole.

At the third level of generalized function, the various processes involved include robotic playing field fabrication processes and the robotic control processes. Further, there are management and organizational processes involved with respect to the functioning of UWNRG, as well as the acquisition and management of resources. In terms of the various physical capabilities of the work domain at the level of physical function, there are entities such as robots, robot playing field, software control setup, electromagnetic/magnetic actuators, roles of the UWNRG members along with the ranks of the patrons assigned by UWNRG (in terms of gold, silver, etc.). Entities at the physical function level will have associated physical form, which is detailed in the next level.

In the level of physical form, the entities include the description of the robot as a ferromagnetic material and robot playing field as etched silicon wafer. In terms of the software control setup, the software language Python is the physical instantiation of the software control systems. Similarly, detailed description of the actuators is also provided. To capture the physical aspects of the UWNRG members and their patron, their condition is highlighted as an entity. Further, the physical form also captures the funds in cash and kind. Along with the above levels, the final level of use-values (affordances) consists of the characteristics of the physical form that could cause malfunction to the entire work domain. In the present case, this level consists of entities which include the fact that robotic playing field may be fabricated improperly; the software can be bug ridden and may not provide proper control during the competition; or, the actuators setup may fail during the completion because of improper control linkage between the hardware and software. In terms of the aspects related to the UWNRG members, there may be difficulty in balancing the schoolwork and UWNRG activities; thus, affecting UWNRG as a whole. Finally, in terms of funding, the there may be restrictions based on the acquisition and usage of funds by certain patrons that results in having effect on the overall UWNRG funding that results in having an effect on the overall UWNRG funding.

Along with the above representation, a causal representation of the RCH environment is also possible and presents a broader insight (RCH 1.1.1, Figure 7.10). In this representation, the two levels of abstract function and generalized function are presented in detail. In case of abstract function, there is a conservation of mass by stoichiometric relations. Therefore, the initial mass of materials results in the final mass by the transfer of mass into different phases in chemical reactions. Along with mass, energy is a conserved quantity in terms of the robot's movement in the magnetic field. This includes the robot having potential energy initially, which is transformed into kinetic energy during movement, and finally back into potential energy when the robot comes to a stop. Finally, there is a reciprocal interaction between the balance of economic values and priorities in the UWNRG group as a whole. A final entity at this level of abstract function are fundamental principles and laws related to the individual projects. As described in chapter 6, these have not been developed in detail.

Along with the abstract function, the level of the generalized function depicts the detailed causal processes. The first causal process consists of the playing field where the silicon wafer is changed into the robotic playing field by the process of etching. In terms of the robotic control processes, the control involves two stages, corresponding to the stages of the competition. In the first stage, the control is automated, while in the second stage it is manual. In terms of the management and organization processes, the first process of recruitment leads to the induction of new members who are involved in the development of communication of knowledge and maintenance of group cohesiveness. Finally, there are processes related to resource management that involve acquiring resources and managing resources for the UWNRG funding. Along with these processes, a final process of maintaining reciprocity with the patrons that enable acquiring resources from these patrons in the future is also prominent.

Along with the above two representations, the third representation consists of the abstraction decomposition space (RCAH 1.1, Figure 7.11). In this representation, the UWNRG is divided into a subsystem and subsystems. At the subsystem level, three subdivisions are created corresponding to technical teams; control teams; as well as business and marketing team. In case of functional purpose, the systemic level has the function of winning robotic competitions. At the level of individual teams the goal is to make functioning robots and playing fields. Similarly, for control teams, the purpose is to make correctly functioning control systems. Whereas, for the business and marketing team the aim is to maintain presence in the UW community as well as obtain and manage funding. Similar to the level of functional purpose, the other levels are discussed in terms of the various subsystems and described in detail in RCAH 1.1.

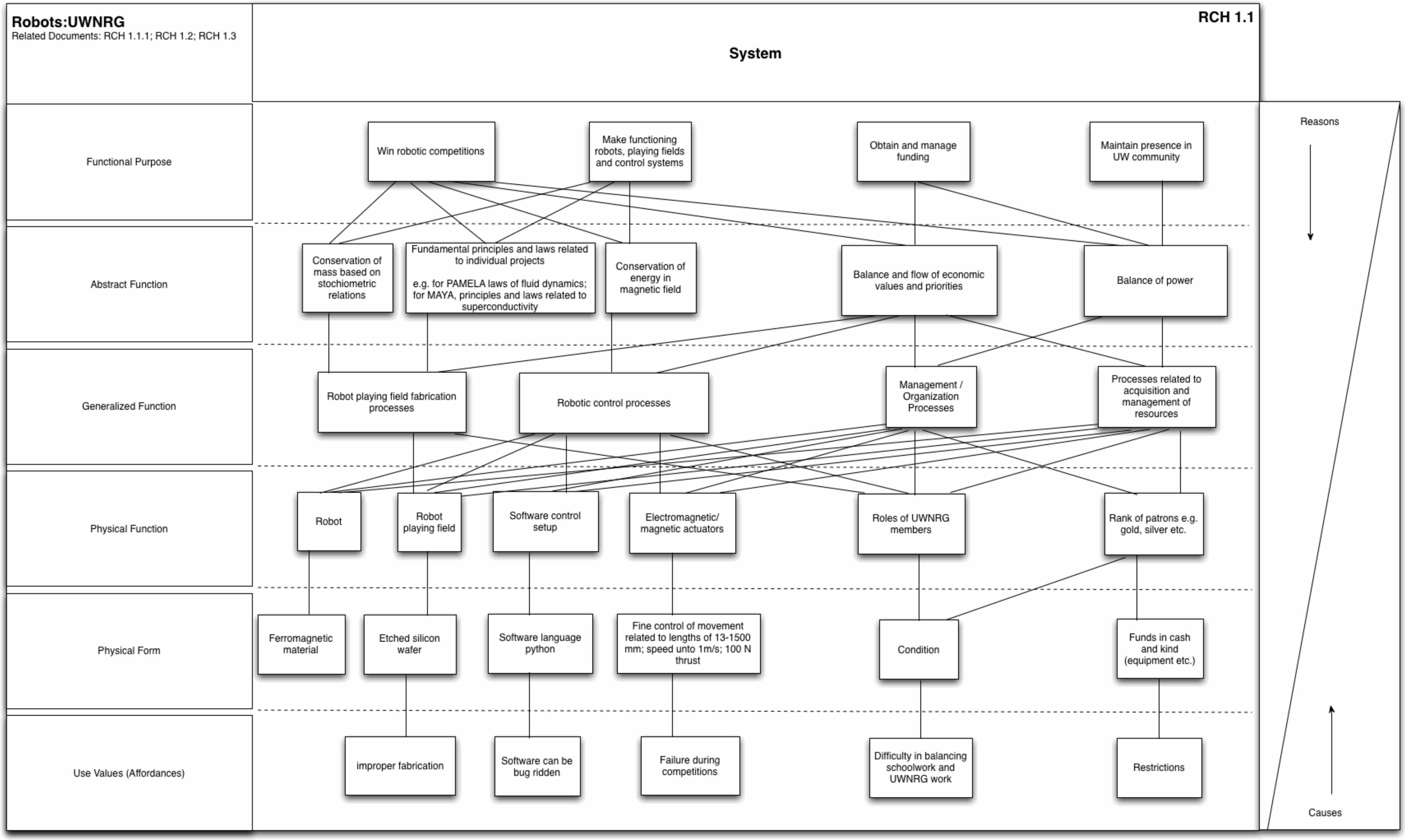


Figure 7.9: RCH environment for UWNRG

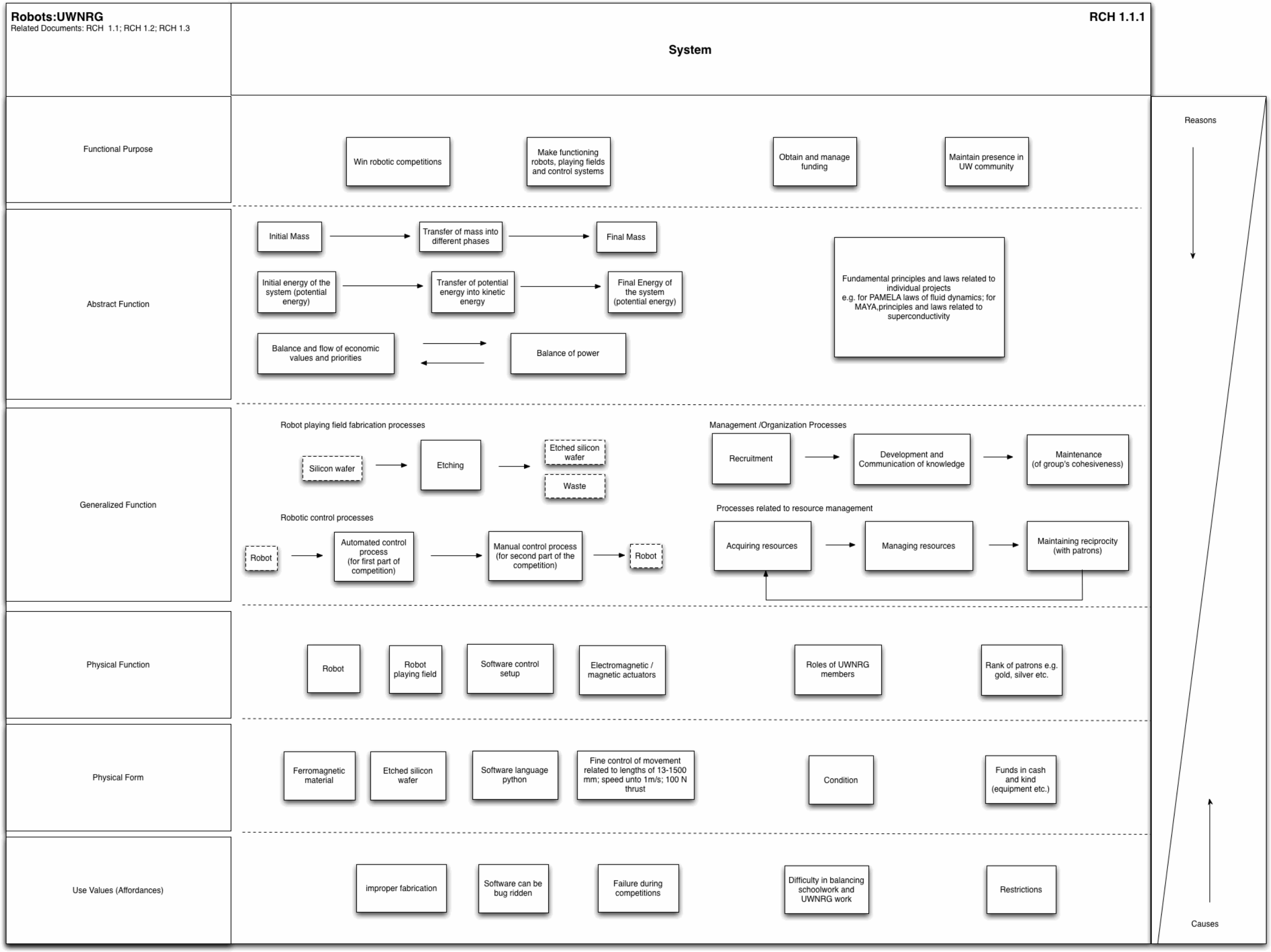
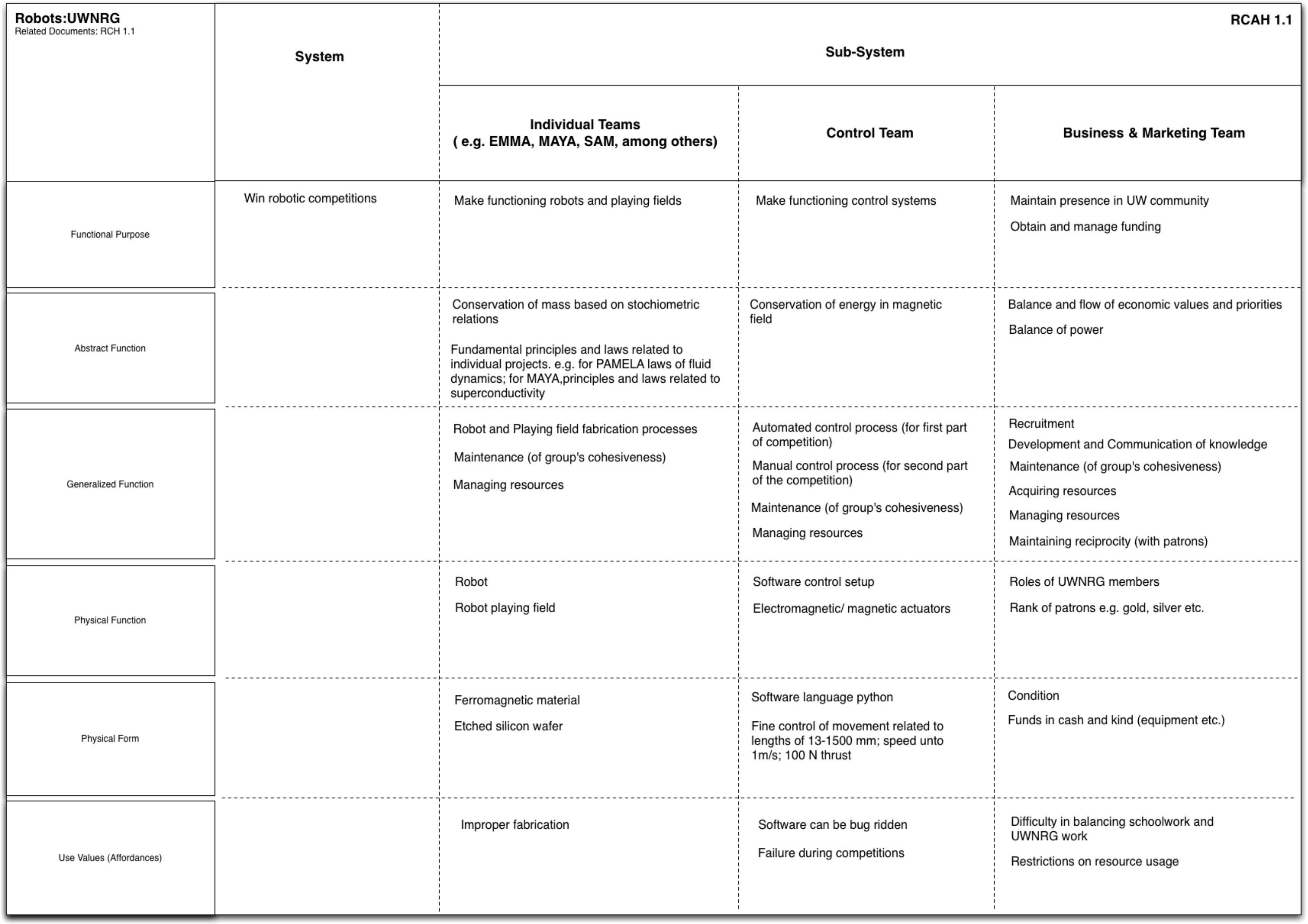


Figure 7.10: Causal representation of the RCH environment



Robots:UWNRG
Related Documents: RCH 1.1

RCAH 1.1

	System	**Sub-System**		
		Individual Teams (e.g. EMMA, MAYA, SAM, among others)	**Control Team**	**Business & Marketing Team**
Functional Purpose	Win robotic competitions	Make functioning robots and playing fields	Make functioning control systems	Maintain presence in UW community Obtain and manage funding
Abstract Function		Conservation of mass based on stochiometric relations Fundamental principles and laws related to individual projects. e.g. for PAMELA laws of fluid dynamics; for MAYA,principles and laws related to superconductivity	Conservation of energy in magnetic field	Balance and flow of economic values and priorities Balance of power
Generalized Function		Robot and Playing field fabrication processes Maintenance (of group's cohesiveness) Managing resources	Automated control process (for first part of competition) Manual control process (for second part of the competition) Maintenance (of group's cohesiveness) Managing resources	Recruitment Development and Communication of knowledge Maintenance (of group's cohesiveness) Acquiring resources Managing resources Maintaining reciprocity (with patrons)
Physical Function		Robot Robot playing field	Software control setup Electromagnetic/ magnetic actuators	Roles of UWNRG members Rank of patrons e.g. gold, silver etc.
Physical Form		Ferromagnetic material Etched silicon wafer	Software language python Fine control of movement related to lengths of 13-1500 mm; speed unto 1m/s; 100 N thrust	Condition Funds in cash and kind (equipment etc.)
Use Values (Affordances)		Improper fabrication	Software can be bug ridden Failure during competitions	Difficulty in balancing schoolwork and UWNRG work Restrictions on resource usage

Figure 7.11: Abstraction decomposition space for RCAH environment

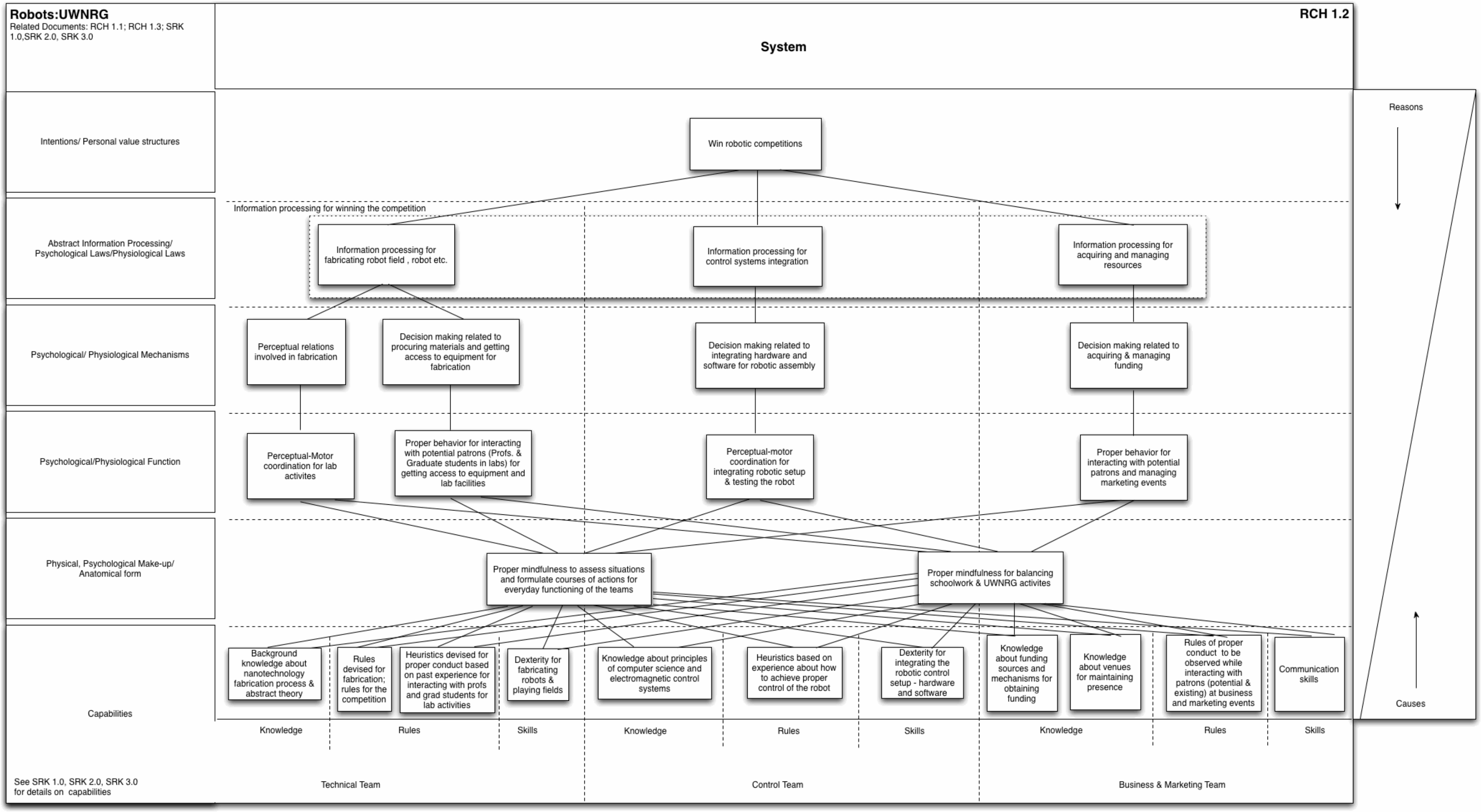


Figure 7.12: RCH Agent for UWNRG robots

7.3.3 RCH Agent

The second hierarchy of WIDF is RCH-Agent (RCH 1.2, Figure 7.12). In the present analysis, the RCH-agent is modeled taking the whole UWNRG as an agent-like entity. Therefore, at the level of the functional purpose, the common intention of all the teams is to win the competition. At the next level, there is information processing required for winning the competition. At the individual team level, the overall information processing involved in winning the competition can be divided into individual team level functioning. Therefore, at this level of the abstract information processing, entities can be subdivided into individual information processing for the teams. Therefore, the technical team involves information processing for fabricating the robot fields, robots, and the like; the control team requires information processing for control systems integration; the business and marketing team requires information for acquiring and managing resources. At the next level of psychological mechanisms, in terms of the technical team, there are perceptual relations involved in fabrication as well as decision making related to procuring materials and getting access to equipment for fabrication. For the control team, there is decision making related to the integration to the hardware and software for the robotic assembly. Finally, in case of business and marketing team, there is decision making related to acquiring and managing funding.

At the level of physiological/ psychological function, for the technical teams, two major entities are present. They are perceptual-motor coordination for lab activities as well as displaying proper conduct for interacting with the potential patrons (such as professors and graduate students in the labs) for getting access to equipment and lab facilities. In case of the control team, they require perceptual motor coordination for integrating robotic setup and testing the setup. Further, for the business and marketing teams, there is a necessity for having proper behavior for interacting with potential patrons and managing marketing events. At the next level of physical, psychological make-up/anatomical form, there are two entities common to all the teams. The first is the need for mindfulness to assess situations and formulate courses of actions for everyday functioning of the teams; second, there is the necessity for proper mindfulness for balancing schoolwork and UWNRG activities.

Finally, at the level of capabilities, the three different teams have different capabilities in terms of skills, rules and knowledge. For example, in case of the technical team, the knowledge required in terms of the background knowledge about nanotechnology fabrication process and abstract theory. In terms of rules, there are rules devised for proper fabrication of the robotics fields. Further, the rules of the competition have to be adhered to while fabricating the robotic fields. Along with these rules, there are heuristics based on past experience devised for proper interaction with the professors and graduate students for lab related activities. In terms of skills, there is dexterity required for fabricating the robots and the playing fields. In case of capabilities of the control team, there is knowledge required about the principles of computer science and electromagnetic control systems. Next, there are heuristics based on experience about how to achieve proper control for the robot. Further, there is the dexterity required for integrating the robotic control setup – hardware and software. The business and marketing teams have knowledge about the funding sources and mechanisms for obtaining funding. Further, they require knowledge for maintaining presence in the UW community. In terms of rules, there are rules required for proper conduct to be observed while interacting with patrons of business and marketing events. Communication skills are also required for business and marketing events. These skills, rules and knowledge required for the various teams are developed further in terms of skills, rules and knowledge categorization for SRK 1.0 (Table 7.9), SRK 2.0 (Table 7.10), SRK 3.0 (Table 7.11).

SRK for the making the robot setup for the competition Related documents: RCH 1.3				**SRK 1.0**
Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge-Based Behavior**

Associated Number	**Associated Number**			
Ultimate Goal / Task	Define Task		Rules about the competition (for e.g. robot and robot playing field, dimensions etc.). Heuristics gained from past experience about schedules for preparing for the competition	Knowledge about nanotechnology fabrication, knowledge about robotics
1,3	2			
Formulate Procedures	Procedures	Planning skills required for allocating tasks among members. Phased planning for steps involving robot making, fund gathering, fund management, competition arrangement, among other phases	Heuristics based on past experience about rough time schedules for the phases to begin and end during academic years	
4	5			
Execute		Dexterity required for fabrication. Presentation skills required for presenting proposals to members of UW community for access to labs and resources		
6				

Observations	Set of Observations	Skills required to gauge the situation and ascertain whether the project is running correctly according to the need, and on time (both on a weekly basis and monthly basis)	Heuristics based on experience about rough time schedules based on previous competitions	
7	8			
Identify	System State	Skills required to gauge whether UWNRG is functioning properly as a group. For e.g. whether the presence of the group is maintained during the weekly meetings, are members doing their work, among other aspects.		Knowledge about project requirements and the whole UWNRG group
9	10			
Interpret, Evaluate	Ambiguity	Skills required to detect flawed situations in regard to UWNRG functioning. For e.g. the members not working or producing the outcomes on time, resulting in project slippages	Heuristics based on past experience for understanding ambiguous situations and possible courses of action to keep the robot creation process on schedule	
11,13	12			

Define Task		Management and planning skills required to reformulate the tasks and plan the situation accordingly. For example, if an equipment is unavailable, then the first step is to search for the equipment, if it is not possible to receive the equipment then new research direction is sought and associated tasks reformulated		Knowledge about the UWNRG group as a whole required to understanding the delegation of tasks and task subcomponents.
14				

Table 7.9 : Skills, Rules and Knowledge required for making the robot

SRK for integrating hardware and software for the control system setup **SRK 2.0**

Related documents: RCH 1.3

Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge-Based Behavior**
Associated Number	**Associated Number**			
Identify	System state			Knowledge of hardware circuits and software language, Python
1	2			
Interpret	Goal State	Perceptual skills/ decision making skills required for detecting problem areas related to the integration of the hardware and software	Heuristics based on past experience about finding possible problems	Knowledge of hardware circuits and software language, Python
3	4			
Define Task	Task	Planning skills required for planning various phases of the tasks of integration	Heuristics based on past experience of the various tasks, allow for providing proper phased approach to control systems integration for the competition	
5	6			

Formulate procedure	Procedure	Planning skills required for allocating resources to each tasks related to the hardware and software setup	Heuristics based on past experience about the members and their motivation and capability. These heuristics are is helpful for allocating the tasks	Knowledge required about the time taken for team members working on the tasks
7	8			
Execute		Dexterity and electronic skills required for setting up control circuit. Programming skills required for coding the algorithm.		
9				

Table 7.10: Skills, Rules and Knowledge required for integrating hardware to software

SRK for obtaining funds and managing reciprocity **SRK 3.0**
Related documents: RCH 1.2

Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge-Based Behavior**
Associated Number	**Associated Number**			
Activation	Alert		Heuristics developed with past experience help with funding. For e.g. there is necessity to enquire whether funding is required at any given point of the project development	Knowledge about funding schedules of agencies such as engineering society (EngSoc) that provides funding on a term-to-term basis
1	2			
Observation	Set of observations	Based on discussion and possible sources of funding, the possibilities of obtaining funding in terms of cash or kind	Heuristics based on past experience about possible good sources to support certain kinds of equipment/ software	
3	4			

Identify	System state	Skills required for gauging the need for funds at the level of individual teams, as well as the overall UWNRG.	Heuristics based on past experience about possibilities of funding from certain patrons depending on the amount of funds and the kind of research funding required	Knowledge is required about the funding capabilities of patrons that have supported UWNRG in the past
5	6			
Interpret	Ambiguity	Skills required for interpreting the current state of funding. Also for discovering and removing ambiguities to form a concrete goal state related to the goals to be accomplished in the short run (weekly) as well as in the long run (monthly), for the competition. Ambiguities may be present due to the unclear reply, or lack of reply from patrons regarding funding; certain policies that may curtail funding		
7	8a			

		for a few materials; among others.		
Evaluate	Ultimate Goal, Goal state	Evaluation of these ambiguities and their removal are done in light of the ultimate goal state of winning the completion. Thus, decision making and planning skills (short terms as well as long term) are paramount at this stage		Knowledge about past patrons and possibilities of future patrons
9a	10a, 8			
Define Task	Task	Planning skills for defining tasks and the manner in which funding agencies are to be approached		
9	10			
Formulate Procedures, Execute	Procedure	Planning and social skills are required for contacting the various patrons and presenting funding proposals		
11, 13	12			

Identify, Formulate Procedure, Execute	Task, Procedure	Interpersonal skills required for formulating the appropriate means of maintaining reciprocity with the patrons. Steps 16- 17 have similar skills depicted in 11-13 above and are not discussed in detail.	Rules for social interchange, heuristics for professional conduct	Knowledge about the past projects in which the patron has provided support as well as knowledge of the UWNRG reciprocity towards them.
14, 16, 18	15, 17			

Table 7.11: Skills, Rules and knowledge required for obtaining funds and managing reciprocity with patrons

7.3.4 RCH Act

The final hierarchy of WIDF consists of the RCH-Act (RCH 1.3, Figure 7.13). In this case, the entire set of acts are modeled together but not divided in terms of individual groups. This is because, in many cases of the acts, the various groups together acted in a manner to bring about the end result. Therefore, labeling the acts as stringently belonging to one group as compared to the other was difficult. The first level of symbolic purposes of the hierarchy consists of devising robots that win competitions. At the next level of information processing/meaning processing, there are four main entities. First, there is the information processing for making robotic setups for the competition (developed in detail in RCH 1.3-DL 1.3.1; Figure 7.14). Second, there is the information processing for integrating hardware and software for the control system setup (detailed RCH 1.3-DL 1.3.2; Figure 7.15). In the third case, there is the necessity of charting the information processing activities related to getting funds and managing reciprocity with the patrons (developed in RCH 1.3- DL 1.3.3; Figure 7.16). Finally, there is information processing for maintaining the team functioning. This is not developed in detail because the maintenance of the team functioning requires the multiple sub-information processing activities and has not been developed in Chapter 6.

In the third level of generalized strategies, there are multiple strategies that include getting equipment, strategies for attracting and retaining labor, strategies for maintaining integrating control systems, among others. To demonstrate the strategies two of these have been developed in greater detail. These include strategies for getting funding for chemicals (RCH 1.3-StrA 3.1; Figure 7.17) and strategies for getting funding from patrons (RCH 1.3-StrA 1.3.2; Figure 7.18). In the fourth level of physical tasks, there are four main sets of tasks. These physical tasks include physical tasks related to developing the robots (RCH 1.3-HTA 1.3.1; Figure 7.19); physical tasks related to getting funding (RCH 1.3-HTA 1.3.2; Figure 7.20); physical tasks related to managing the control team; and physical tasks for setting up the control team systems (RCH 1.3-HTA 1.3.3; Figure 7.21). Further, along with the physical tasks, there are automatic adjustments related to the task demands, which is captured in the fifth level of automatic changes. Finally, the acts have the possibilities of being misinterpreted, for e.g., during interaction with clients, misinterpretations of acts could lead to loss in the funding (level of interpreted value).

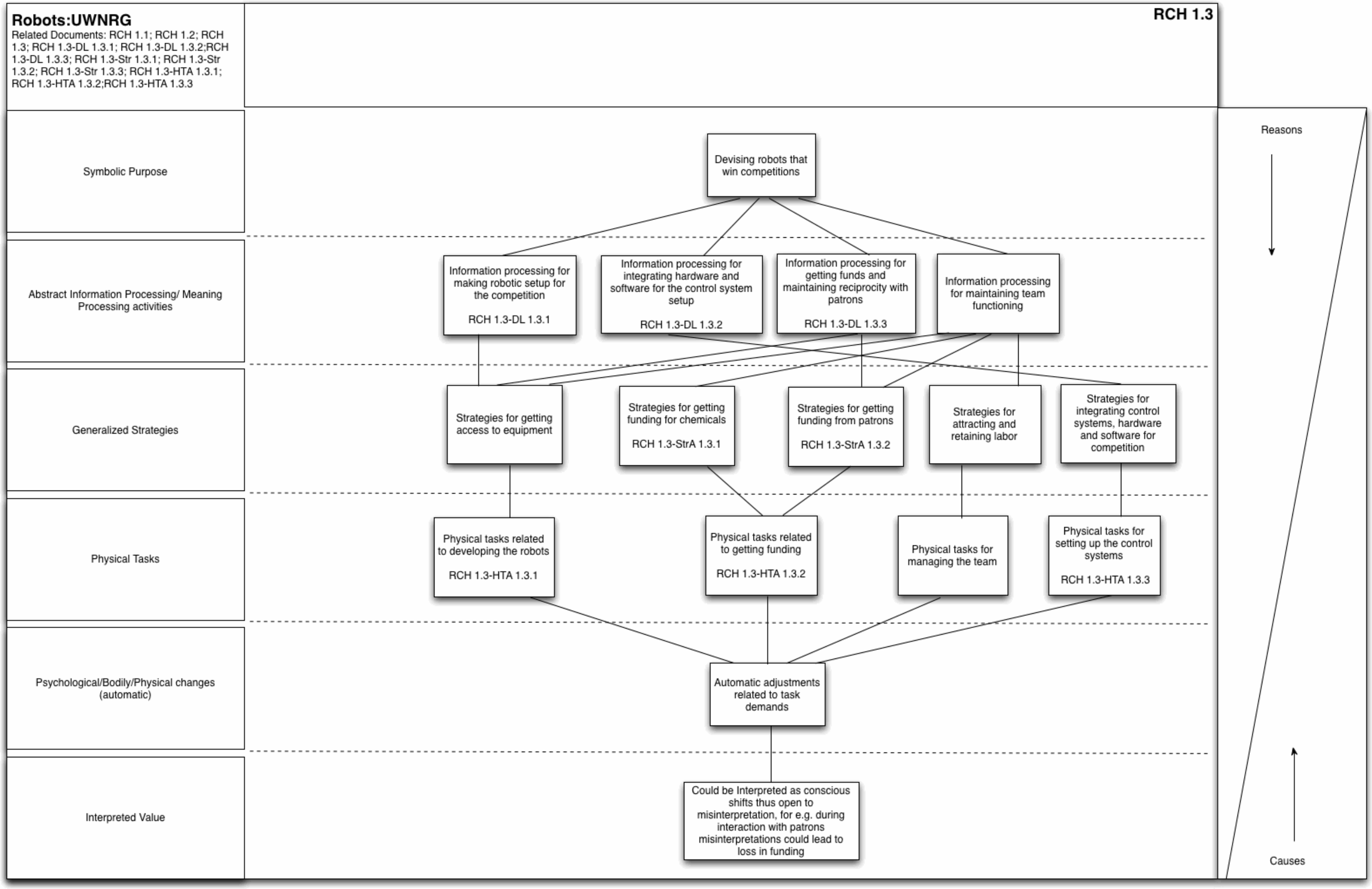


Figure 7.13: RCH Act for UWNRG

Information processing for making robotic setup for the competition

RCH 1.3 - DL 1.3.1

Related documents: RCH 1.3

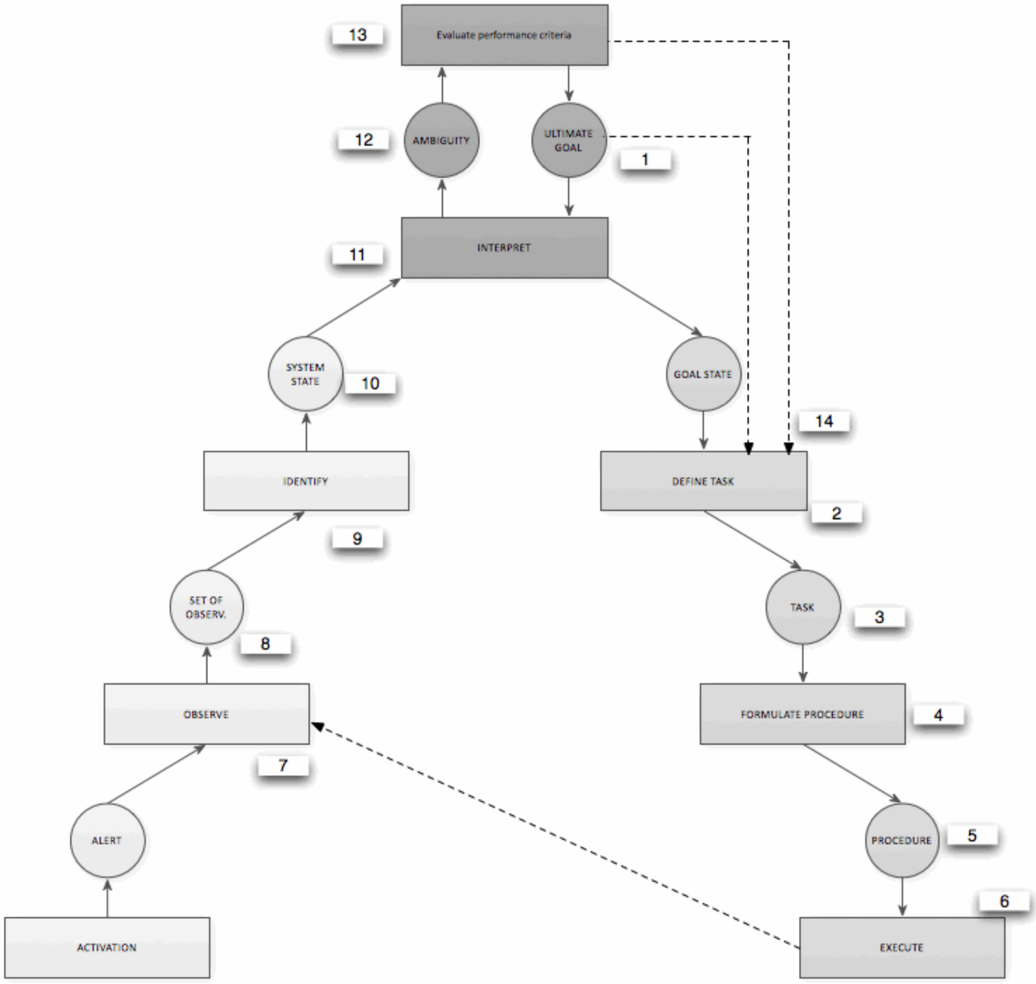


Figure 7.14: Information processing activities for making robotic setup competition

Information processing for integrating hardware and software for control systems **RCH 1.3 - DL 1.3.2**

Related documents: RCH 1.3

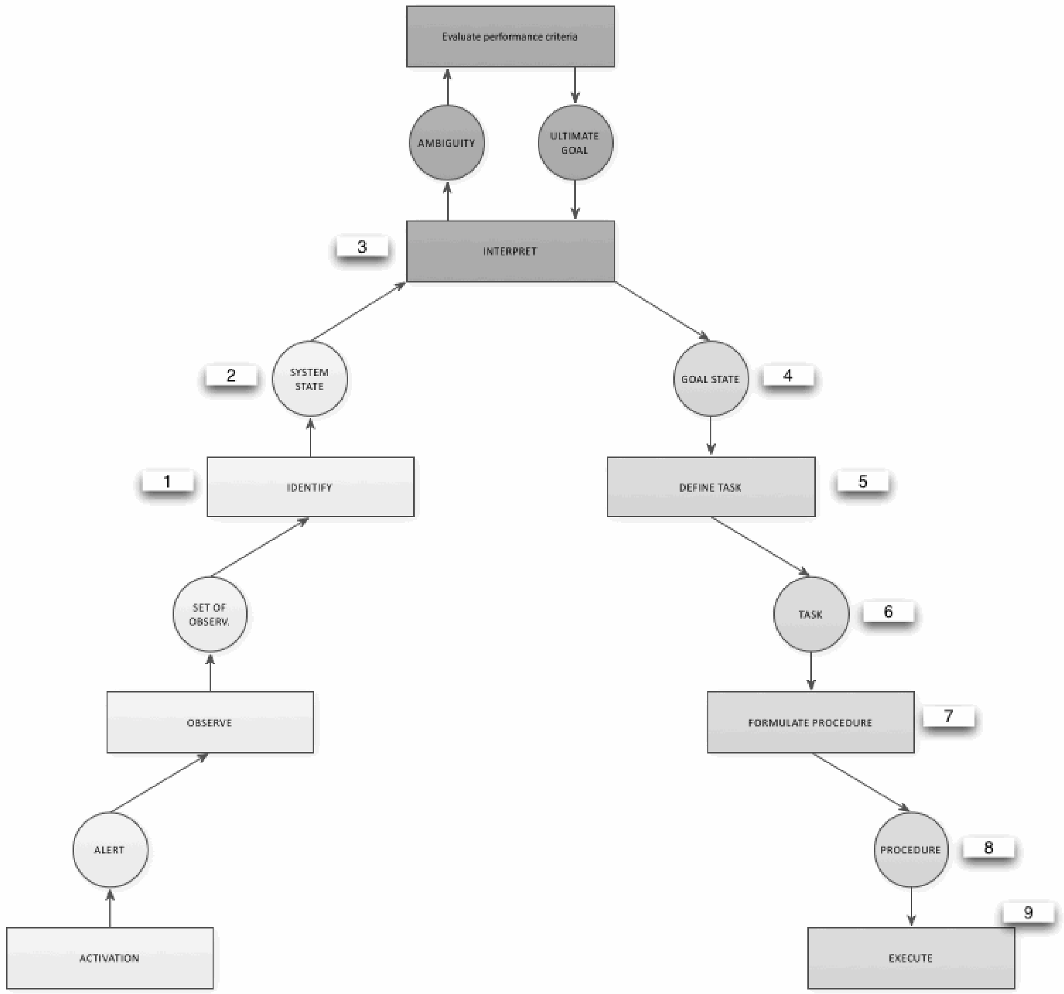


Figure 7.15: Information processing for integrating hardware and software for control systems

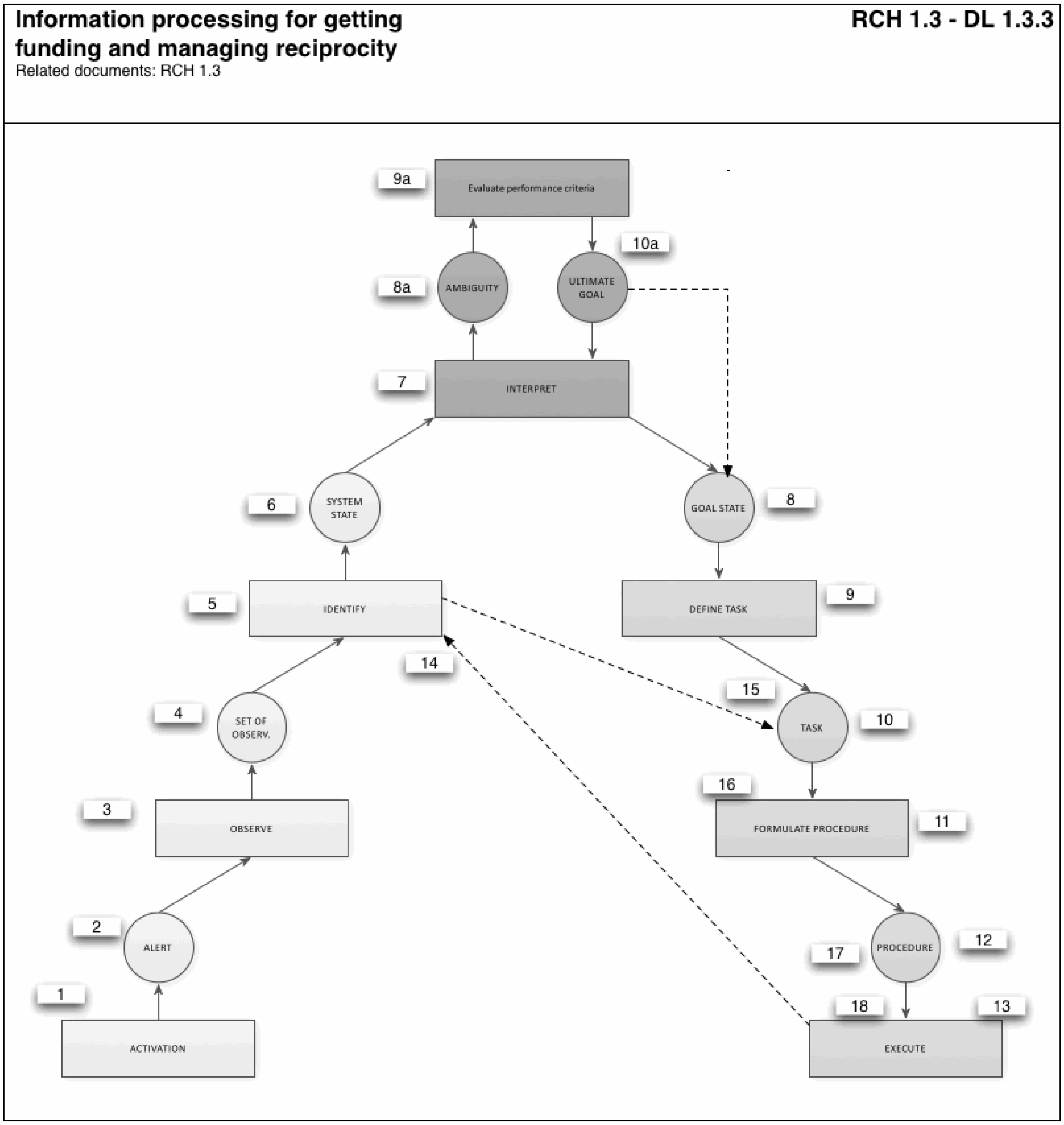


Figure 7.16: Information processing for getting funding and managing reciprocity

Strategies analysis for getting access to chemicals **RCH 1.3- StrA 1.3.1** Related documents: RCH 1.3	
1	In the first strategy, the aim is to obtain funding in cash. Since the mobility of cash is possible, the UWNRG members often divert some cash obtained for other products towards purchasing chemicals. The chemical purchases are typically made at the chemistry stores at UW.
2	The second strategy for obtaining chemicals is employed when the chemicals required for the individual projects are of lesser quantity and the work on the projects are at a preliminary stage of experimentation, often involving many different ideas and ways to fabricate the robots. In this case, the team members who conduct fabrication in particular laboratories ask for the use of chemicals. Due to the small amount of chemicals used, UWNRG members often get the chemicals for free. In case of expensive chemicals, UWNRG takes into account some mechanisms for paying the price of the chemicals, to the lab. Thus, getting access to chemicals.
3	The third strategy consists of getting chemicals to be funded by the patrons. As described before, not all funding agencies provide money for perishable products and materials. The use of chemicals has to be highlighted in terms of the robot design process. Thus, establishing the value of the perishables product in terms of the final non-perishable product. Therefore, obtaining funding from patrons for buying chemicals

Table 7.12: Details of strategies for getting access to chemicals

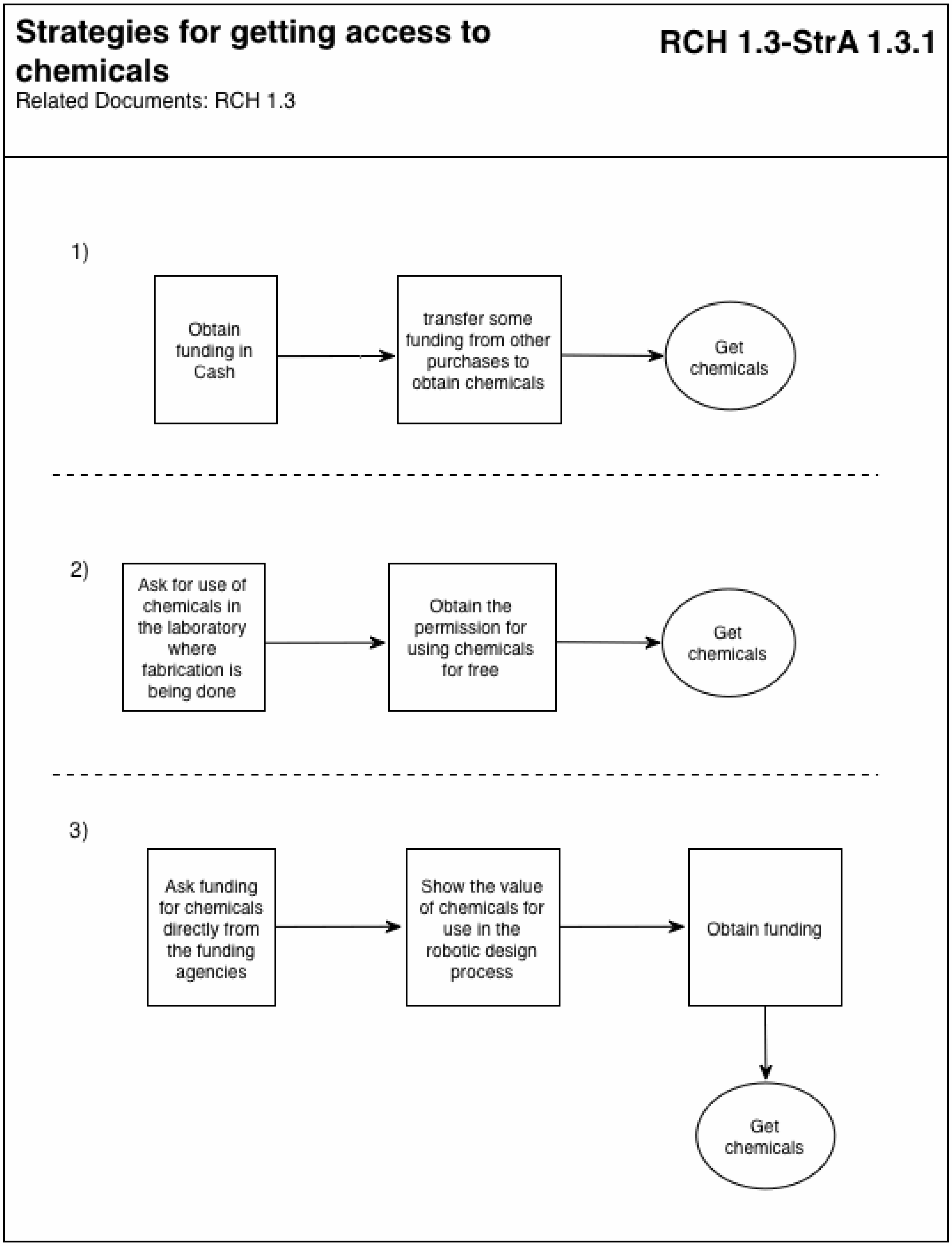


Figure 7.17: Strategies analysis for getting access to chemicals

Strategies analysis for getting funded by patrons **RCH 1.3-StrA 1.3.2** Related documents: RCH 1.3	
1	The first strategy involves contacting patrons directly and requesting for funding in cash. In the process, the business team provides a presentation about UWNRG and its goals. By persuasive arguments, the business team receives funding
2	The second strategy for getting support, involves contacting patrons and requesting them for particular equipment or software. In the process, the business team provides a presentation to convince the patrons to provide funding. If successful, the patron provides the funding in terms of equipment or software.
3	The third strategy for funding involves getting renewed support from patrons who have provided funds in the past. In order to get refunded in the future, the marketing team highlights the patrons by providing coverage in social media. Further, after winning competitions, the sponsors are highlighted in interviews and websites. Further, the marketing and business teams follow up with the patrons and send them gifts to show gratitude for the support they have provided in the past. This enables the channels of support to remain open for future cases and aids in UWNRG to get funding.

Table 7.13: Details for strategies for getting funding from patrons

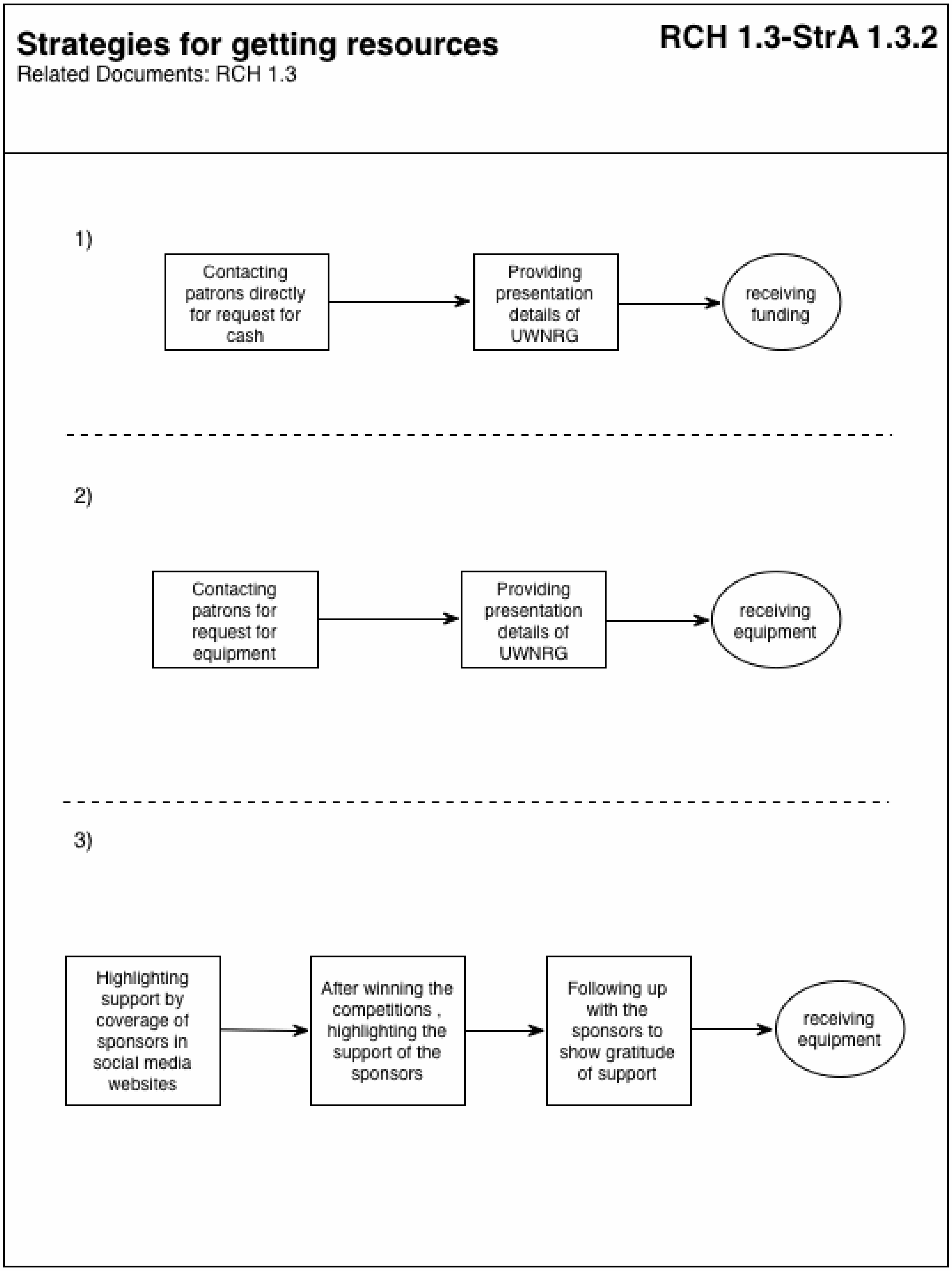


Figure 7.18: Strategies analysis for getting resources

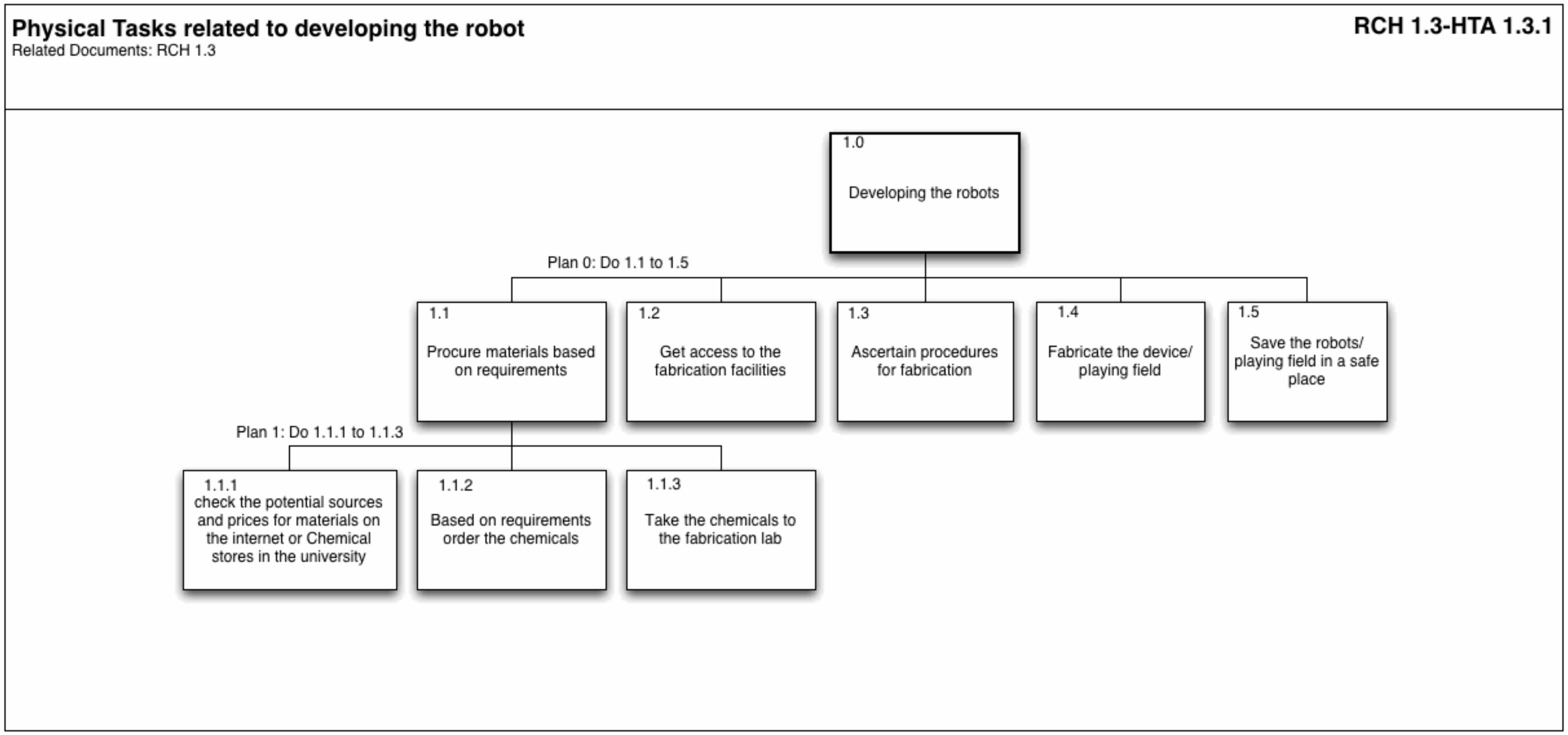


Figure 7.19: HTA for the physical tasks for developing the robot

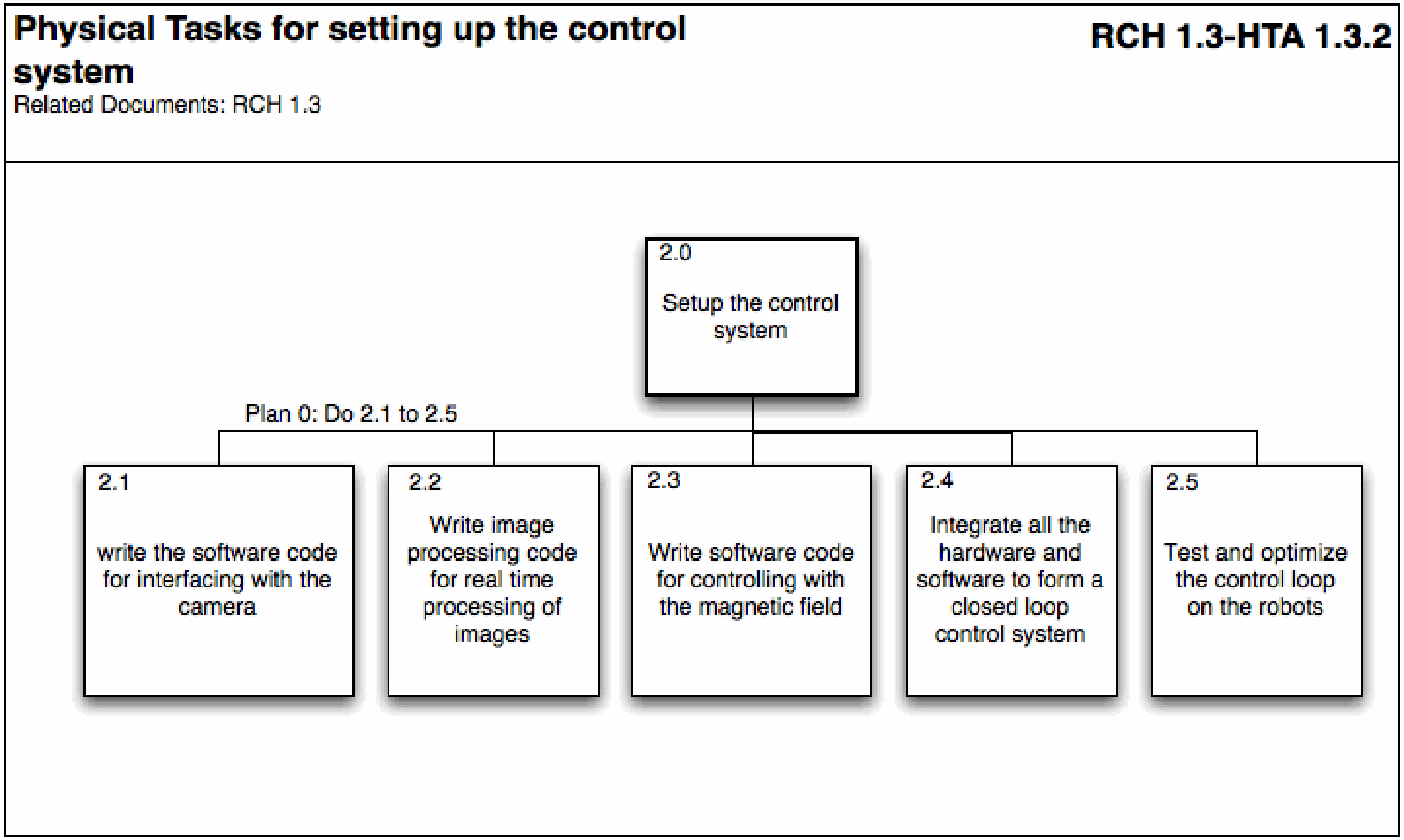


Figure 7.20: HTA for physical tasks for getting funding

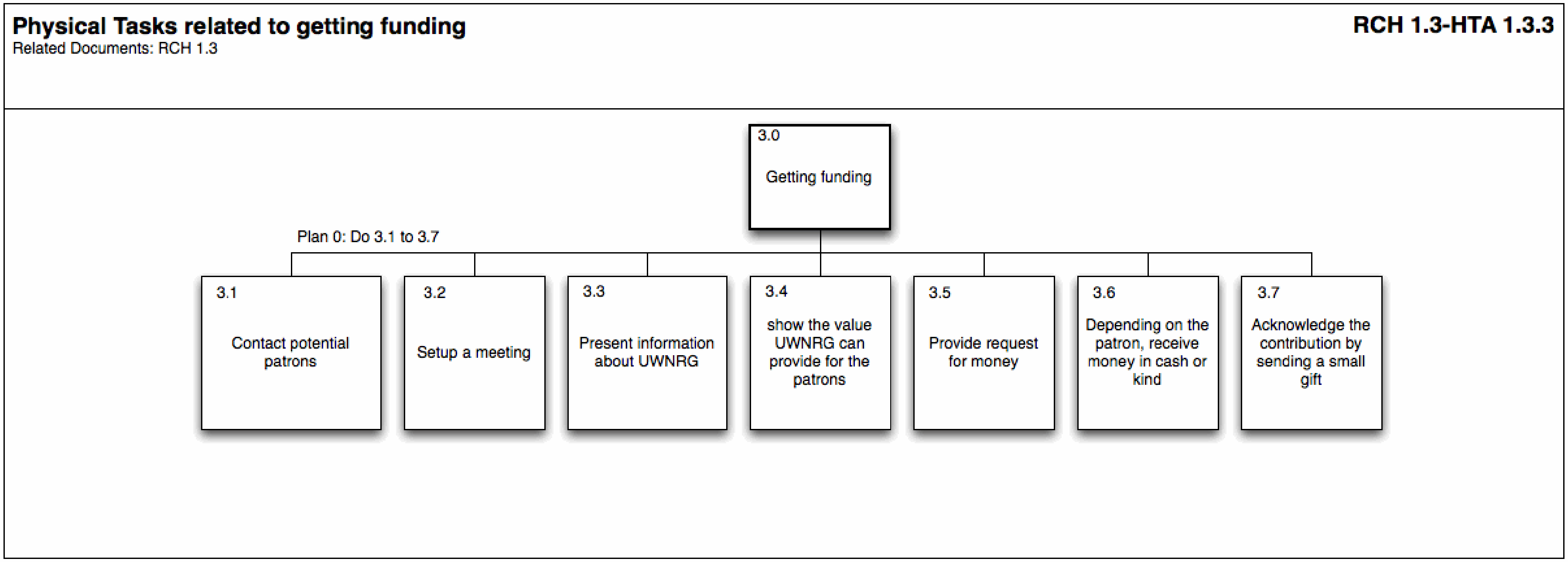


Figure 7.21: HTA for setting up the control system

7.4 Comparison between CWA and WIDF

Comparison between WIDF and CWA for UWNRG			
	Comparison Criteria	**WIDF**	**CWA**
	RCH Environment (equivalent to AH in CWA)	Present	Present
21.	Functional Purpose	• Win robotic competitions • Make functioning robots, playing fields and control systems • Obtain and manage funding • Maintain presence in UW community	• Win robotic competitions • Make functioning robots, playing fields and control systems • Obtain and manage funding • Maintain presence in UW community
22.	Abstract Function	• Conservation of mass based on stochiometric relations • Fundamental principles and laws related to individual projects • Conservation of energy in magnetic field • Balance and flow of economic values and priorities • Balance of power	• Conservation of mass based on stochiometric relations • Fundamental principles and laws related to individual projects • Conservation of energy in magnetic field • Balance and flow of economic values and priorities • Balance of power
23.	Generalized Function	• Robot playing field fabrication processes • Robotic control processes • Management /Organization Processes • Processes related to acquisition and management of	• Robot playing field fabrication processes • Robotic control processes • Management /Organization Processes • Processes related to acquisition and management of

Comparison between WIDF and CWA for UWNRG			
	Comparison Criteria	**WIDF**	**CWA**
		resources	resources
24.	Physical Function	• Robot • Robot Playing field • Software Control Setup • Electromagnetic Actuators/Magnetic actuators • Roles of UWNRG members • Rank of patrons e.g., gold, silver etc.	• Robot • Robot Playing field • Software Control Setup • Electromagnetic Actuators/Magnetic actuators • Roles of UWNRG members • Rank of patrons e.g., gold, silver etc.
25.	Physical Form	• Ferromagnetic material • Etched Silicon wafer • Software language python • Fine control of movement related to lengths of 13-1500 mm; speed unto 1m/s; 100 N thrust • Condition • Funds in cash and kind (equipment etc.)	• Ferromagnetic material • Etched Silicon wafer • Software language python • Fine control of movement related to lengths of 13-1500 mm; speed unto 1m/s; 100 N thrust • Condition • Funds in cash and kind (equipment etc.)
26.	Use value (affordances)	• improper fabrication • Software can be bug ridden • Failure during competitions • Difficulty in balancing schoolwork and UWNRG work • Restrictions	
	RCH for Agent	Present	Not present as a whole except for SRK

Comparison between WIDF and CWA for UWNRG			
	Comparison Criteria	**WIDF**	**CWA**
27.	Intentions/ Personal Value Structures	• Win robotic competitions	
28.	Abstract Information Processing / Psychological Laws/ Physical Laws	• Information processing for fabricating robot field, robot etc. • Information processing for control systems integration • Information processing for acquiring and managing resources	
29.	Psychological Mechanisms	• Perceptual relations involved in fabrication • Decision making related to procuring materials and getting access to equipment for fabrication • Decision making related to integrating hardware and software for robotic assembly • Decision making related to acquiring & managing funding	
30.	Physiological Function	• Perceptual-Motor coordination for lab activities • Proper behavior for interacting with potential patrons (Profs. & Graduate students in labs) for getting access to equipment and lab	

Comparison between WIDF and CWA for UWNRG			
	Comparison Criteria	**WIDF**	**CWA**
		facilities • Perceptual-motor coordination for integrating robotic setup & testing the robot • Proper behavior for interacting with potential patrons and managing marketing events	
31.	Physical, Psychological Makeup/Anatomical form	• Proper mindfulness to assess situations and formulate courses of actions for everyday functioning of the teams • Proper mindfulness for balancing schoolwork & UWNRG activities	
	Capabilities (equivalent to SRK in CWA) Technical Team		
32.	Skills	• Dexterity for fabricating robots & playing fields	• Dexterity for fabricating robots & playing fields
33.	Rules	• Rules devised for fabrication; rules for the competition • Heuristics devised for proper conduct based on past experience for interacting with profs and grad students for lab activities	• Rules devised for fabrication; rules for the competition • Heuristics devised for proper conduct based on past experience for interacting with profs and grad students for lab activities
34.	Knowledge	• Background	• Background

Comparison between WIDF and CWA for UWNRG			
	Comparison Criteria	**WIDF**	**CWA**
		knowledge of nanotechnology, fabrication and abstract theory	knowledge of nanotechnology, fabrication and abstract theory
	Capabilities (equivalent to SRK in CWA) Control Team		
35.	Skills	- Dexterity for integrating the robotic control setup - hardware and software	- Dexterity for integrating the robotic control setup - hardware and software
36.	Rules	- Heuristics based on experience about how to achieve proper control of the robot	- Heuristics based on experience about how to achieve proper control of the robot
37.	Knowledge	- Knowledge about principles of computer science and electromagnetic control systems	- Knowledge about principles of computer science and electromagnetic control systems
	Capabilities (equivalent to SRK in CWA) Business & Marketing Team		
38.	Skills	- Communication skills	- Communication skills
39.	Rules	- Rules of proper conduct to be observed while interacting with patrons (potential & existing) at business and marketing events	- Rules of proper conduct to be observed while interacting with patrons (potential & existing) at business and marketing events
40.	Knowledge	- Knowledge about venues for maintaining presence	- Knowledge about venues for maintaining presence - Knowledge about

Comparison between WIDF and CWA for UWNRG			
	Comparison Criteria	**WIDF**	**CWA**
		- Knowledge about funding sources and mechanisms for obtaining funding	funding sources and mechanisms for obtaining funding
	RCH -Act	Present	Not present as a whole (except for Decision Ladder and Strategies Analysis)
41.	Functional Purpose	- Devising robots that win competitions	
42.	Abstract information processing/ Meaning Processing Activities (equivalent to Decision Ladder in CWA)	- Information processing for making robotic setup for the competition - Information processing for integrating hardware and software for the control system setup - Information processing for getting funds and maintaining reciprocity with patrons - Information processing for maintaining team functioning	- Information processing for making robotic setup for the competition - Information processing for integrating hardware and software for the control system setup - Information processing for getting funds and maintaining reciprocity with patrons - Information processing for maintaining team functioning
43.	Generalized Strategies (equivalent strategies analysis in CWA)	- Strategies for getting access to equipment - Strategies for getting funding for chemicals - Strategies for getting funding from patrons - Strategies for attracting and retaining labor - Strategies for	- Strategies for getting access to equipment - Strategies for getting funding for chemicals - Strategies for getting funding from patrons - Strategies for attracting and retaining labor - Strategies for

Comparison between WIDF and CWA for UWNRG			
	Comparison Criteria	**WIDF**	**CWA**
		integrating control systems, hardware and software for competition	integrating control systems, hardware and software for competition
44.	Physical Tasks	• Physical tasks related to developing the robots • Physical tasks related to getting funding • Physical tasks for managing the team • Physical tasks for setting up the control systems	
45.	Bodily/Physical changes (automatic)	• Automatic adjustments related to task demands	
46.	Interpreted Value	• Could be interpreted as conscious shifts thus open to misinterpretation, for e.g. during interaction with patrons misinterpretations could lead to loss in funding	

Table 7.14: Comparison between WIDF and CWA for Site 2

7.5 Conclusion

In chapter 6, the ethnography corresponding to the first step of WIDF was presented. In this chapter, the second step corresponding to the WIDF was conducted. Due to the nature of the domain under consideration, the UWNRG was modeled as a self-sustaining agent-like entity whose main aim was to win robotics competitions. To fulfill this primary aim, the robotics team was divided into sub-teams with different tasks ranging from fabrication of the robot to acquisition and management of resources. To demonstrate the requirements gathering capacity of WIDF, it was compared to CWA. The results show that due to the structure of the hierarchies of WIDF, it allows for more requirements in terms of the body-based cognitive activity and socially situated acts to be gleaned from the domain under consideration. In the next chapter the third and final instance of nanotechnology, presented in this thesis, is discussed.

Chapter 8: Site 3—Materials (Ethnographic Study)

8.1 Introduction

The aim of this chapter is to present the ethnographic study of nanomaterials as used in civil engineering. Thus, it serves as the first step of the extended CWA (WIDF) and provides a holistic understanding of the work domain. Nanotechnology is expected to bring about changes in infrastructure in fundamental ways. This will be possible in a dual manner. First, as demonstrated in the first two research sites, by the creation of new devices, materials and related technologies. Second, as this chapter indicates, a fundamental change can be brought about in already existing devices and materials. This chapter considers the role of nanotechnology in materials (for a broader list of nanotechnology and materials, see CPI, 2014). The focus of this chapter is on nanoconcrete in pavement design. Pavement engineering is a branch of civil engineering that studies and designs roadways, streets and highways, using asphalt for flexibility, and concrete for rigid construction of pavements, among others. Specifically, this chapter aims to highlight the use of nanomaterials in Portland Cement Concrete (PCC) pavements.

Concrete is one of the most ubiquitous materials known to human kind. It is defined as "mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials" (ACI, 2013, p.16). Concrete is simultaneously a material as well as a medium for expression. Engineers and architects find the tension inherent in concrete and its use both as a building material and as a medium for architectural expression (for a historical treatment of concrete for a medium of expression, see Forty, 2013). With the introduction of novel materials at the nanoscale, the bulk properties of concrete are expected to change in terms of durability, compressive strength, and sound-absorption capabilities, among others.

The focus on nanoconcrete in pavement engineering was chosen in this thesis for three main reasons. First, a major driver of transportation and HFE research is the need to increase safety, reliability and resilience of roadways and transport systems. FHWA recognizes both nanotechnology research and information sciences research as areas that cut across all the focus areas and they are expected to provide an increasing convergence with already existing scientific and technological advantages. In the area of materials, FHWA highlights the need for "new approaches in materials science to produce innovative new highway materials with characteristics that enable enhanced functionality (including multi-functionality), constructability, sustainability, cost effectiveness or operating characteristics of highway infrastructure and system monitoring sensors to enhance highway safety, reliability, and resilience" (FHWA, 2014).

A second reason for research in this area is because of the ubiquity of concrete as a material. In fact, "it is the second most consumed material after water" (WBCSD, 2009, p. 7). Further, along with concrete being one of the oldest building materials, the concrete industry is expected to grow steadily as infrastructural demands increase. It is expected that the production of cement, one of the most important ingredients of concrete, will have a yearly growth of 0.8-1.2%. It is expected that by the year 2050, the quantities could reach anywhere between 3700-4400 MegaTonnes, resulting in an increase of production anywhere between 43-72%. (WBCSD & IEA, 2009b, no pagination; also see IEA & WBCSD, 2009a for detailed report).

Third, the use of nanomaterials in an already existing technology will demonstrate how nanotechnology is subtly integrated in our everyday lives; thus, it presents a contrast with the previous two research sites. The first two research sites focus on novel devices and technology while the present chapter presents a reexamination of the old, in light of the new. Nanomaterials in the concrete industry are expected to increase as health related challenges are addressed and the use of nanotechnology in working environments becomes safer. Further, the use of nanotechnology will also increase, as there is a reduction in price of nanomaterials and there is a concomitant growth in the quality control procedures and standards for use of nanoconcrete as a ubiquitous construction material.

In terms of HFE as a discipline, nanoconcrete will affect research areas in transportation systems, environmental design, as well as present opportunities for design of devices and their related interfaces. The US National Science & Technology Council (NSTC, 2014, p. 15) emphasizes that nanotechnology holds great promise for transportation research in providing support for “Safety, Livable Communities, State of Good Repair, Economic Competitiveness, and Environmental Sustainability”. Nanotechnology is expected to provide synergistic exchange among areas such as the development of new types of materials for coating and casting; as well as the development of new nanosensors that could be embedded in highways, allowing for safe transportation. Across the Atlantic, the European Union recognizes the key role concrete will be play in building Europe’s future (BCG, 2013; CEMBREAU, 2013). For example, as compared to asphalt, use of concrete on roadways accounts for 6% less fuel emissions from heavy traffic loadings. The durability of concrete requires less maintenance and repair; thus it accounts for less traffic congestion. Concrete starts becoming cost advantageous between its seventh to fourteenth year of usage as compared to asphalt. Finally, the lower reflectivity of concrete allows for reducing warming effect in urban areas (CEMBREAU, 2013). These properties of concrete allow it to be recognized as a key technology for supporting the European goal of sustainable development of the future.

For HFE, a crucial insight to be gained from this study is that to understand the role of nanomaterials, one should understand the disciplinary embedding matrix. Unlike the first two research sites, which have the capability to generate their own problem areas and solutions, the study of nanomaterials invites an understanding into how the changes at the nanoscale of the material affects its macroproperties. Thus, in the process, nanomaterials lose their identity and change a part of the identity of the overarching field of study, in this case civil engineering. In other words, the study which started with a focus on nanotechnology *per se* ended up being understood as a part of civil engineering.

Nanotechnology applications in concrete should be viewed in terms of the changes that are ongoing in this industry. In order to improve the sustainability, efficiency and performance of concrete, the US Strategic Research Council's roadmap for the year 2030 presents the need for research into three main areas: reuse and recycling of older materials, measurement and prediction, and new materials. Nanotechnology is classified as the research taken under the initiative of new materials.

Currently, four nanomaterials are often used to modify the concrete: nano-silica (nano-SiO_2), nano-titanium dioxide (nano-TiO_2), carbon nano-tubes (CNTs) and carbon nano-fibres (CNFs) (Safiuddin, Gonzalez, Cao & Tighe, 2014; also Sanchez & Sobolev, 2010). All these different materials provide different macroscale properties to the concrete. In terms of macro properties, Nanoconcrete provides greater strength and structural stability; thus, improving the design of built structures. For example, nanoconcrete has been used in the design of bridge in Wappelo County, Iowa, USA. The nanoconcrete in this bridge enhances structural strength by providing for the development of ultra-high-performance bridge components. Nanoconcrete also provides improved aesthetics for building design. For example, white cement containing TiO_2 nanoparticles has self-cleaning photo catalytic properties (Birgisson, Mukhopadhyay, Geary, Khan & Sobolev, 2012). This allows for the maintenance of aesthetic appearance of the buildings. The "Dives in Miscericordia" church in Rome uses white cement containing photo catalytic properties that maintains its aesthetic appearance (Birgisson *et al.*, 2012, p. 22).

As nanotechnology use becomes more widespread in civil engineering it will generate novel areas of research and require solutions to make nanoconcrete cheap and widespread. Birgisson and colleagues (Birgisson *et al.*, 2012, p. 25) identify a few future challenges for nanotechnology research in concrete; such as addressing energy requirements for bulk processing, among others. A few of their requirements fall under the rubric of HFE research. For example, a major challenge for nanomaterials in concrete is to gauge quality control of nanosilica (particle size and morphology). Proper quality control, ensuring the correct size of the nanoparticles and morphology at the nanoscale, is important for observing bulk properties at the macroscale. Currently, as the following study will reveal, the method of understanding the size and morphology of nanosilica in cement was done by the use of imaging techniques, such as a Transmission Electron Microscope (TEM). The charge for using a TEM is CAD$ 70/hr in a university setting of a western developed country. As nanoconcrete becomes more ubiquitous, there will be a necessity for developing cheap imaging techniques for devices that could be used robustly in the fieldwork in developing countries. Further, imaging techniques and novel devices could provide homogeneity and quality metrics by cheap imaging of cement-based materials. These products will be geared towards the global markets hence should be sufficiently inexpensive. The current state of cement, which is an important aspect of concrete, shows that the consumption is highest in China (almost half of the global consumption). It is expected that between the years 2015 to 2030 the consumption in China will peak. After 2030, countries such as India and other developing countries in Africa and Middle-East will present a strong demand (WBCSD & IEA, 2009a, 2009b). Thus, nanoconcrete presents a viable area of study for understanding nanomaterials for the purposes of the future of HFE.

Concrete is a composite material. A composite material is made of two or more materials having different physical and chemical properties, when combined produce a material with different characteristics as that of the individual materials. Further, the individual components may remain distinct and separate in the finished structure. Nanocomposites significantly differ from normal composite materials; for example, in mechanical terms, they have an exceptionally high surface to volume ratio. Such a situation, as will be shown in this study, allows the addition of a small amount of nanomaterials while presenting a greater amount of change at the macroscale (for issues of scale see Sobolev & Gutirrez, 2005, p. 16, Fig. 5).

In the present study, nanosilica is added to concrete to produce a material with enhanced macroscale properties. The following study is divided into two parts depending on the locations where the research is conducted — laboratory activities and field activities. Such a distinction should be seen as a continuum in civil engineering rather than categorical. As it was revealed in the course of the study, at times, the field functioned as the lab.

8.2 Lab Setup

The concrete samples were made in the concrete lab in an area which had proper drainage facilities. This area also had coarse and fine aggregates available. There was a weighing machine that was used for the weighing the materials before the concrete mixing process. The abrasion tests were performed in this area of the lab. The compression testing was done at a different area of the lab because of the location of the compression-testing machine. The British Pendulum test and the sand patch test were done in another lab because the equipment was located there. Similarly, the sound absorption test required a quiet space and the equipment was installed in a corner room in a different building.

8.3 Safety

Working with concrete can be quite corrosive, therefore, all researchers wore gloves at all times during the molding process. The researchers also wore eyeglasses and NIOSH recommended safety masks for working with nanomaterials. Another necessity in this lab was safety boots and at times earplugs. Even though I was an observer, I had to wear safety boots all the time in the concrete testing lab. During the field activities, along with the safety boots, a hard hat and reflective vests were worn at all times.

8.4 Details of the Fieldwork

Similar to site 1, in site 3, the major approach was observation. The period of observation lasted for about two months (second week of June to second week of August, 2013). The total number of officially logged hours amounted to around 102 hours. Unlike site 1, the tasks in site 2 were more group-oriented and I could observe the combined activity of many members together at any given time. In short, I was following the entire group. Similar to site 1, in site 3, a large amount of useful information obtained was from informal conversations and hanging out with civil engineers. However, the procedure of data collection was not completely limited to observation. While involved in the fieldwork for site 3, during one of the data gathering sessions held outdoors, one member of the team did not show up. This member was involved in tasks such as lifting and moving equipment. Due to this situation, I ended up filling the role of the missing member. This chance was fortuitous as it provided me with an insight to be a part of the team during their work. In site 3, due to the nature of the work, the major discussions were reserved for the beginning and the ending of the work session.

8.5 Research Activities

8.5.1.1 Lab Activities

Researchers in civil engineering laboratories conduct research on nanoconcrete by making samples and testing these samples to understand how properties of concrete behave macroscopically. The following account presents the research activities in a civil engineering lab and provides insight into how research is conducted in relation to nanoconcrete.

Figure 8.1: Nanoconcrete sample for pavement engineering and nanosilica sample on display

8.5.1.1.1 Activity of making samples

Concrete, unlike other materials, requires considerable labor and is typically produced at the place where the concrete is to be used. The process of concrete mixing requires considerable human intervention. Even though concrete is a fairly robust composite, it still poses a considerable risk while being formed in the laboratory for experiments. As this study reveals, making concrete samples used for research purposes requires considerable workmanship, for concrete changes shape - it moves from being formed as a liquid to, after curing, becoming a solid. This material, thus, requires considerable workmanship. In contrast to the “workmanship of risk” in site 1, this workmanship is best labeled as the “workmanship of certainty”. In “workmanship of certainty”, the end result is known and the amount of risk involved is not as great as the “workmanship of risk” (Pye, 1968, Ch. 2). However, there is still a considerable amount of dexterity, judgment and care involved in making concrete samples for the testing process.

As the participants of this study were civil engineers, their approach towards nanotechnology was to understand how these nanomaterials changed the macroscopic properties of concrete. The first step in this approach was to make concrete samples, which would be later used for testing purposes. Since this area of research was new, a particular procedure was designed for the concrete formation process. For making samples, coarse aggregate and fine aggregate is mixed along with water in a particular ratio. These materials are put into a rotary mixer and mixed for one minute. Aggregates are inert materials that form 60-75% of the concrete. Aggregates may include materials such as sand, gravel, and recycled concrete, among others. To ensure a proper mix, these materials should be clean and strong, i.e., not flaky. Further, their composition should be such that they are chemically inert and free of chemicals that would lead to the degeneration of concrete in the long run. Aggregates can, typically, be divided into two categories — coarse and fine. Coarse aggregates typically have particle size varying between 0.375 to 1.5 inches in diameters. In this regime, gravel serves as a good choice for aggregates. Along with coarse aggregates, the fine aggregates are those particles with diameters less than 0.375 inches. They typically pass through a sieve that stops the coarse aggregates. Natural sand or crushed stone serves as a good choice for fine aggregates. Aggregates influence the concrete's properties in terms of grading; durability; particle shape and surface texture; abrasion and skid resistance; weights and voids in a unit; as well as absorption and surface moisture. In this lab, natural sand was used as a fine concrete and gravel as coarse aggregates. The fine and coarse aggregates are mixed using a rotary mixer along with water for one minute.

Figure 8.2: Materials for making samples

Figure 8.3: Rotary mixer for concrete mixing

Once this mixture is obtained, there is a need for adding air bubbles in the concrete. This intentional creation of air bubbles is necessary for improving the behavior of the concrete during the freeze-thaw cycle. Typically, after the water is used up in the chemical process that leads to the formation of concrete, the extra water evaporates, leading to small pores in the concrete. Basically, this makes the concrete a porous material. When this concrete is exposed to moisture, the water turns into ice. Ice occupies about nine percent more volume than water. Thus, resulting in the expansion of the water as it freezes. This repetition of freezing and thawing, expands and contracts the concrete; thus, leading to early deterioration. To counteract the freeze-thaw cycle, inclusion of air voids act as stress relief. Many small voids separated at equal distances would be adequate for handling freeze-thaw cycles. Air entraining agents are added to create stable air bubbles. These air entrainment agents are chemicals having properties that allow their molecules to be attracted to air bubbles at one end and cement grains to the other. Thus, they end up providing a coating of calcium from around each air bubble thus ensuring the overall air entrainment in the concrete. After the air entrainment agent is added along with water, the mixture is rotated for a minute to mix them thoroughly. The next step is to add cement and nanosilica along with 0.25 parts of water and mixed for three minutes. It is ensured that nanosilica is first mixed with water and then added to the mixture rather than directly in powder form. This is done to mix it properly with concrete and also avoid its escaping in dust form.

Figure 8.4: Concrete being mixed in the mixer

Researchers like good workmen are attuned to the mixing process. One researcher brought my attention to the subtle sound changes of the mixer that describe the changes in the process. The sound of the mixer changes as the materials inside the drum change as the process is underway. After adding the nanosilica, there comes about a change in the sound of the mixer. The sounds seemed prolonged and slow as the rotor blades of the mixer belabor against a dense material. The researchers attuned to the sound recognize that the nanosilica makes the mixture dense thus indicating that the process is underway.

Addition of the Portland Cement with water to the above mixture is the key to the development of concrete as a composite; thus, aiding the chemical process of hydration. The above mixture is covered with wet burlap for three minutes. The burlap is provided to avoid moisture loss and also to aid in the hydration process. Once the cement is mixed with water, the chemical process of hydration begins. In this process the dry cement changes chemically in contact with the water to form a paste and adheres to the adjacent aggregates. This process is key for making the concrete unique in terms of its transformation from a paste-like state to a solid state. In its paste-like state, the concrete is malleable and shows plasticity, whereas, in the solid state, it is hardened and durable. The process of mixing the various materials of concrete are not entirely passive, as the researcher is actively attuned to the process of mixing the material.

Figure 8.5: Wet burlap placed on concrete to aid hydration process

Finally, to this malleable paste, a chemical admixture was added along with 0.25 parts water and mixed for three minutes. Admixtures are chemical ingredients added to concrete to ensure certain properties of the concrete such as ensuring the quality of concrete during mixing and transporting, among others. These admixtures can also be classified according to their functions such as air-entraining, water-reducing, retarding and accelerating the process of concrete production or acting as plasticizers. Plasticizers reduce the water content in the concrete in order to make high-slump flowing concrete. The viscosity of concrete allows it to be used for making samples with very little vibration and excess compaction. As a result, this makes the process more economical. Typically, the addition of plasticizers (or superplasticizers), depending on the brand, has an effect lasting anywhere between 30-60 minutes, after which the workability of the concrete decreases. In the process used in this lab, a high-range water reducer (HRWR) was used as an admixture in the concrete. This made the concrete workable.

After adding the HRWR, a slump test is performed to gauge the consistency of the concrete. The consistency of the concrete is gauged so as to be in accordance with the requirements of the finished product. Thus, if there is less water then it makes the concrete difficult to work with; however, at the same time it provides more durability to the finished product. On the other hand, the concrete with more water makes it more fluid but provides a softer and less durable finished product. In order to gauge the consistency of concrete, a slump test is performed. A slump test consists of filing a mold with concrete. This mold is filled with concrete and using a rod, the concrete is penetrated with rapid thrusts, straight downwards, for it to settle properly. It is ensured that the thrusts are not so deep so as to reach the base of the mold. If the thrusts reach the base of the mold, then they may create voids which do not fill up properly. Therefore, extreme care is taken in settling the concrete for the slump test. The mold is filled to the brim and the extra is wiped off the top layer to level it. Once this is done, the mold is lifted so as to reveal the concrete. The mold is then placed very near to the concrete, but not on it, and a horizontal rod is taken and placed next to concrete with a straight edge laid on the top edge of the mold. The difference in length (in inches) between this straight edge and the top of the mold is the “slump” of the concrete. The “slump” indicates the height loss when the concrete settles down. Depending on the requirements, the results of the slump test are interpreted.

Figure 8.6: Slump test being performed on the concrete to ascertain workability

Along with the slump test, the air content test was also performed. Previously, in the mixture, air entraining agents were introduced to intentionally add air. The challenge is to ensure that air entrainment has been conducted successfully and has not been overdone. Excess air reduces the strength of the concrete. One percent increase in air, typically, reduces the strength by three to five percent. To ensure proper air strength a calibrated air meter (Type B) is used. The air meter is a cylindrical instrument in which the concrete is poured and the result is read on a dial.

The above is the description of making a concrete mix and ensuring relevant properties in fresh conditions in order to be used for casting. This above delineated process entails considerable human effort and dexterity. Even though the process is fairly robust, in some instances, it can be fragile. The concrete making process can be affected by change in air conditions and the temperature. In the concrete mixing area in the lab, there was door leading to the outside. This door was at times used by others for entry or exit. This change in air quality had an effect on the concrete mix. Further, the process of concrete mixing is not mechanistic. It requires considerable care and constant intervention to ensure the workability of the concrete mix.

Once the concrete is removed from the rotary mixer, there is a flurry of activity due to the short time available in which the slump test and the air content test have to be conducted. This is due to the fact that workability of the concrete has to be retained, for it to be good for the molding process. Also both the slump test and air content test have to be done with extreme care. For example, in the slump test, there is a necessity for the mold to be removed straight upwards without any torsion or lateral motion in a time not more than five or ten seconds. The above aspects indicate the “workmanship of certainty” that is involved in the process of making concrete. As noted before, the outcome of the “workmanship of certainty” is apparent. However, to achieve the outcome takes great care, judgement and dexterity on part of the people involved in the concrete making process. On a typical day involving the molding process, three batches of concrete are typically prepared, having quantities of 0%, 1% and 2% nanosilica, respectively. Preparation of these batches requires considerable endurance from morning till around four in the afternoon with a short half an hour break for lunch. In this batching process, three people were involved. However, large batching requires more pairs of hands. In situations where large batches are to be prepared, other lab members are called to lend a hand.

The “workmanship of certainty” is also observed in the process of creating samples with the freshly created concrete. The concrete is poured into samples and a long metal rod is used to poke the concrete so that it settles properly and leaves no air voids. Avoidance of air voids is extremely crucial to the process of making concrete samples. Later, since these cylindrical samples are used for strength testing, air voids provide erroneous results. Thus researchers take extreme care in ensuring all voids are absent. In order to avoid voids, the researcher pokes the concrete in the middle as well as the sides, as most of the samples end up with voids on the side. A further consideration is not to poke the concrete too deeply so as not to penetrate the layer near the bottom of the mold. These considerations have to be balanced while making the samples. Molds often differ based on the project requirements. For the project involving nanosilica, two sizes were used. One cylinder was vertically short and horizontally broad; the other, vertically long and horizontally less broad. These cylinders were coated with a release agent (chemical) that prevents the adhesion of the freshly made concrete with the plastic mold.

Figure 8.7: Plastic molds washed and are made ready for concrete to be poured

The fresh concrete is then poured into the molds and the surface is given a finish using the required texture. Concrete surfaces can be given a flat finish or a different texture depending on the requirement. In the molds used for this study, the samples are either given a plain finish, using a trowel, or a broom finish. In a trowel finish, a hand held trowel (a tool with a handle and a flat surface) is used to make the top of the edge smooth. The planing requires considerable dexterity and care in order to make the top smooth at an equal level. In contrast to the trowel finish, in a broom finish, a hand held broom is used to mark the texture on the face of the mold. Similar to the trowel, in case of the flat broom finish, considerable care is taken to make the finish even; i.e., the hand is held steady to make the grooves at an equal depth from the surface.

Figure 8.8: Molds being poked by a rod to enable the settling of concrete

Figure 8.9: Molds being given a plane surface finish

Once the concrete has been poured into molds, it is covered with a large plastic sheet and left for twenty-four hours. The plastic sheet is placed to stop the concrete from excessively dehydrating and being disturbed while it dries. After these twenty-four hours, the concrete samples are demolded. The demolding requires considerable dexterity. Typically, the demolding requires hitting the molds with a hammer to loosen them. Thus, this facilitates the release of the concrete form. Researchers have different, often idiosyncratic, approaches. One researcher highlighted that hitting the concrete too hard during the demolding process would taint the results of the strength test. Therefore, the researchers used a method of demolding in which a pointed chisel was placed at the centre of the bottom side of the mold and rapped slightly. Next, compressed air was passed through the point where the pointed chisel was used under the bottom surface of the mold. Two further raps were made on the sides of the mold. This was strong enough to loosen the mold. In contrast other researchers hit the mold hard at the bottom and the sides to loosen the concrete. This may at times have a detrimental effect on the concrete. Once the samples are released, it may be found that some surfaces were not even, i.e., the samples were not regular. The surfaces of the samples had to be ground to make them regular. This regularity was needed later for the compression test in which both faces of the cylindrical mold had to be parallel so that the force could be applied evenly.

Figure 8.10: Strategy for demolding

Figure 8.11: Air being passed from the bottom for easy demolding

Figure 8.12: Molded concrete samples (after seven days)

Figure 8.13: Molded concrete samples with flat surface

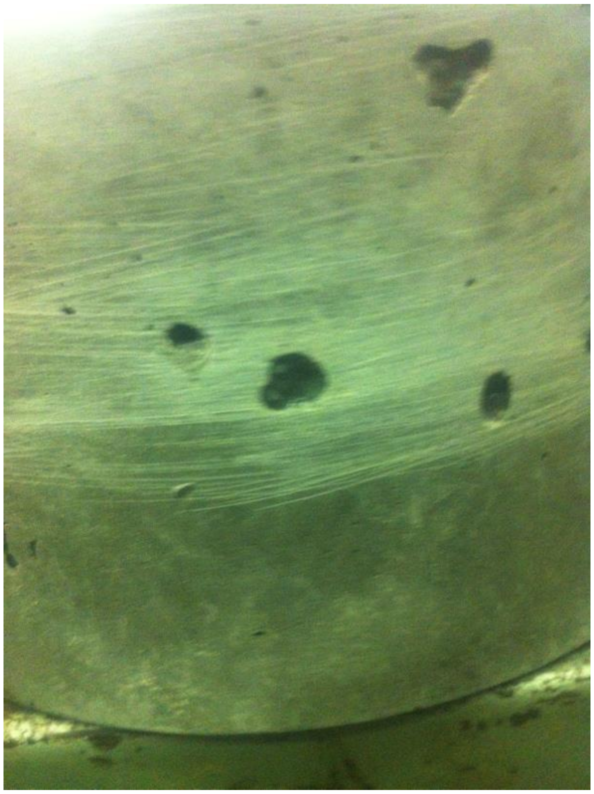


Figure 8.14: Air voids formed in the concrete sample (found after demolding)

Figure 8.15: Humidity chamber for curing. Notice the thin jet of water from the top of the room to provide constant humidity

Figure 8.16: Samples placed in the humidity chamber for curing

Curing is a process in which concrete is protected from drying up quickly. The loss of moisture is curtailed by placing the concrete in a humidity-controlled room. Good curing allows the concrete to develop slowly and enhance its strength. This cured concrete will be tested later. Typically in concrete testing, the samples are tested after seven, fourteen or twenty-eight days (according to standards). In this project, involving nanosilica, two different sets of samples were used for testing. One set was tested after seven days and the second after twenty-eight days. Since the testing period involves a whole month of waiting, the researchers ensure that each process of concrete making and molding is carefully created and voids are avoided.

8.5.1.1.2 Activity of testing samples

Once the samples were ready for testing, they were subjected to a battery of tests to understand their macroproperties. These tests require a considerable amount of knowledge about the correct operation of instruments as well as the knowledge about how the samples are to be set up for proper experimentation. Therefore, as the following tests reveal, lab experiments in civil engineering requires both "thing knowledge" (Baird, 2004) of test equipment as well as knowhow of how to properly conduct the experiment. Since these tests are common fare in civil engineering, this knowhow is second nature to the researcher.

In order to understand the macro properties, the following tests were conducted: Compression test; Sound absorption test; British pendulum test; Sand patch test; and Abrasion test. Further, along with macroproperties, to ensure that the nanosilica had proper size and morphology at the nanoscale, imaging tests were also conducted. The compression test identifies the load bearing capacity of the concrete sample. Thus, this informs the researcher about the possible changes brought about in the strength of the concrete samples by the addition of the nanomaterials during the formation stage. Addition of nanomaterials also brings about changes in sound absorption capabilities of the concrete. To measure this property, a sound absorption test can be conducted. Along with sound absorption properties, it is also expected that the addition of nanoparticles improve the surface related properties, such as friction and surface texture. To ascertain friction, a British Pendulum test was performed; the macro surface texture was gauged by a sand patch test. Along with these surface properties, a related property is that of wear and tear in pavements. To simulate this wear and tear, an abrasion test was performed. The above tests were focused on macroproperties. Along with these tests, nanomaterial research in concrete pavements requires a quality check at the smaller scale. A standard challenge is to ascertain whether the nanomaterials have been mixed with concrete at the smaller scale. Therefore, imaging tests are conducted to ensure the size and morphology of the nanosilica samples.

8.5.1.1.2.1 Activity of conducting a Compression test

Earlier, it was pointed out that based on specifications, two sets of samples were made — one tall and the other short. The tall ones were used for strength tests, while the shorter ones were used for all the remaining tests. This division was made because a comprehensive strength test required adherence to certain standards for quality control. For example, the cylinders should be of appropriate dimensions. They should be dry before testing. Further, they should have parallel faces. Many times, after the molding process, the faces of the long cylindrical samples are not parallel. Thus, they have to be leveled in the grinding machine to have parallel faces. This is required to ensure that the force applied in the compression test is evenly distributed. If the samples do not comply according to the standards, then the effort of the twenty-eight days may end up being wasted. Therefore, such considerations form a key concern during the testing process.

During the compression test process, the cylinders are placed properly so as not to deviate from the center, therefore, they will receive an equal distribution of the applied force. After this placement, the top surface of the compression board is slowly brought into contact with the top of the mold. This serves as the zero point. After this, the force is applied to the mold up until the point, where the mold cracks; i.e., fails to handle the compressive force. Once the compression test begins, the researcher has his eyes trained on the dial as to note the exact reading at which the concrete cylinder fails the test. Often the concrete cylinders disintegrate, the readings are noted and the samples discarded.

8.5.1.1.2.2 Activity of conducting a Sound Absorption test

After the compression test used the longer samples, the sound absorption test, is conducted on the shorter samples. In this test, a metal tube is present in which sounds are emitted at one end and the concrete sample is placed at the other. The difference between the sound emitted by the microphone and the sound reflected by the concrete is recorded to calculate the amount of sound absorbed by the concrete. Sound absorption is a key macroproperty of concrete, and has direct impact on road noise pollution. In this test, the samples are fixed onto a sound tube where at one end there is a sound emitting device. The sound emitted and reflected from the concrete are recorded by the presence of two microphones to gain an insight into the amount of sound absorbed by the concrete. For conducting the test, the concrete mold is fixed at one extreme corner of the sound absorption equipment. The test is conducted using software that is also used to record and store the data. After the test, the samples are removed from the device.

Figure 8.17: Ensuring that the compression head of the machine merely touches the top of the surface before beginning the test

Figure 8.18: Sample placed in the machine before the test

Figure 8.19: Cracked sample, after the compression test

Figure 8.20: Sound absorption test equipment

Figure 8.21: Fitting the mold into one end of the equipment

Figure 8.22: Tightening the mold for proper results in the experiment

The test is fairly straightforward; however, it presents problems at times. There was a particular case which presented a challenge for the researchers. A few samples were not completely circular. This resulted in the samples not fitting properly into the round aperture of the tube. As a result, to accommodate that sample, the packing around the tube had to be carefully maneuvered to fit the sample snugly. In another case the concrete sample was slightly more elliptical than usual; it had to be discarded. To investigate this problem, the researchers went back to the original plastic mold and found a slight disfiguration. This mold was later replaced. Therefore, even though the tests are fairly straightforward, they still present considerable unanticipated challenges.

8.5.1.1.2.3 Activity of conducting a British Pendulum test

Imagine driving on a rainy day on a highway and applying the brakes suddenly. The force developed when the tire is prevented from rotating and hence slides is called the skid resistance. Minimizing skid events is crucial for averting accidents. A method of gauging skid resistance in concrete is by the British pendulum test. This apparatus has a pendulum attached to a base. A standardized piece of rubber is fitted at the pendulum bob. The concrete sample is fixed at the base in such a manner that the rubber base of the pendulum bob grazes slightly over the surface of the top surface of the concrete, which is wetted. While the pendulum slides, it moves another pointer to a concomitant distance. The reading of this second pointer allows for converting skid resistance to a numerical scale.

In conducting the test in the lab, two researchers operate in a team which allows them to minimize the time required for the tests. The first researcher fixes the mold to the base where the device is placed and adjusts the mold height in relation to the pendulum such that the bob just grazes the surface of the mold. Then the first researcher wets the top surface of the mold. Using a temperature gun, the second researcher notes the reading of the surface. The first researcher then proceeds with recording data for the test and verbalizes the readings. Three readings are taken. The second researcher notes these readings. After the first researcher has completed the first mold and is in the process of adjusting the second mold in the device, the second researcher takes the first mold and arranges them under a blast of air from a fan to make them dry faster. This allows the researchers to work in tandem and reduce the time.

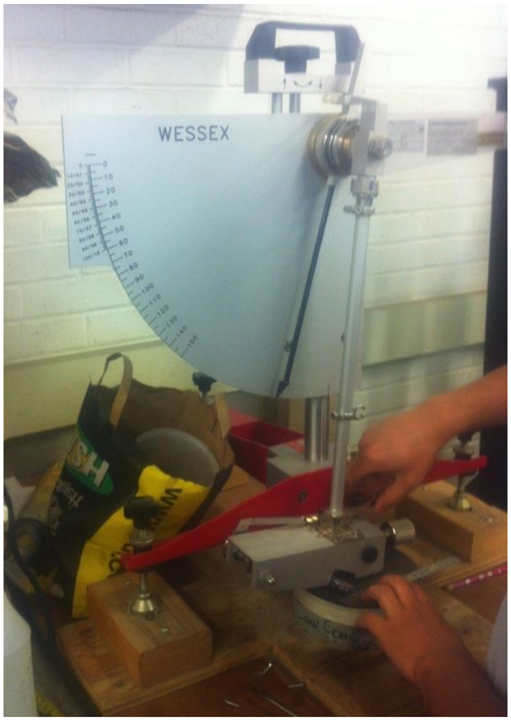


Figure 8.23: Nanoconcrete sample being setup in the British Pendulum Test

Figure 8.24: Sample being wetted to simulate wet roadway conditions

The British pendulum test is a simple test that is quite often and easily used in fieldwork. One of the key challenges in conducting this test is to align the concrete mold with the lower part of the pendulum bob correctly. If improper alignment occurs then the researcher will obtain spurious results. In order to avoid this situation, researchers tend to align the sample properly before conducting the test.

8.5.1.1.2.4 Activity of conducting a Sand Patch test

Sand Patch test is used to understand the depth of the texture of the concrete. Once the mold is dry after the British pendulum tests, the sand patch test is conducted on them. In this test, a fixed volume of glass beads (or graded sand) is taken and carefully spread in a circular fashion to form a circular patch. The diameter of the sand is noted and is used to calculate the depth of the patch. The sand patch test proves as a simple yet effective technique for gauging the texture of the roadways. The main concern in the sand patch test is that the circular motion should be maintained in order to spread the patch properly. If the patch is not quite circular then the measurement goes awry. This requires eye-hand coordination. Novices at this task often find it difficult to achieve proper circles. This step though simple requires considerable dexterity.

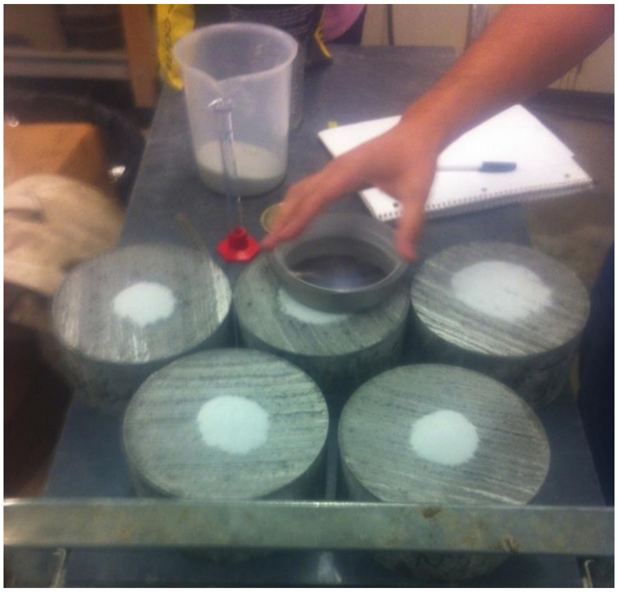


Figure 8.25: Spreading the sand in a circular form

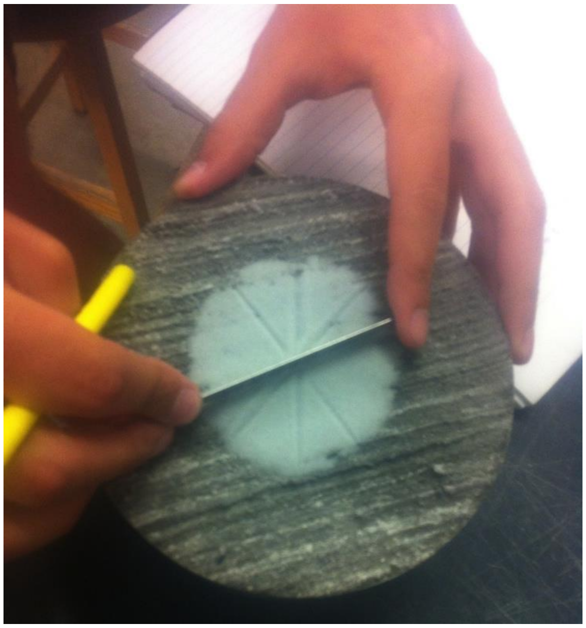


Figure 8.26: Taking readings in a sandpatch test

8.5.1.1.2.5 Activity of conducting a Abrasion test

Another crucial macroproperty of the concrete is its resistance to wear and tear. In order to gauge this phenomenon, the concrete mold is initially weighed. Then it is placed in a setup (shown below) that has a rotating chuck with mechanical cogs attached. These mechanical cogs are brought into contact with the upper face of the concrete for a designated time (depending on the project requirements). After that designated time where the upper surface succumbs to the abrasion, the extra dust is blown off. Later the concrete is weighed again to ascertain the amount of material loss. The weight of material loss is used for calculation of the resistance of concrete to abrasion. This test requires operating the machinery and handling the heavy setup is a task undertaken by two researchers.

Figure 8.27: Setting up the abrasion test equipment

Figure 8.28: Rotatory head used for the abrasion test

In this test, first, the mold is weighed before the test. Next, it is secured properly to a fixed base. Next, the machine is switched on which begins rotating the cogs. The researcher brings down the rotating cogs very slowly and places them in a position in which they come in contact with the surface of the concrete mold. This position is maintained for two minutes. After this time the rotating cogs are slowly separated from the surface and the machine is switched off. The mold is then removed after the abrasion test and the dust is cleaned with a blast of compressed air. The weight of the mold after the abrasion test is noted and later the mold is discarded.

Figure 8.29: Abrasion test in progress

Figure 8.30: Cleaning the mold with a blast of air to get rid of the dust after the abrasion test

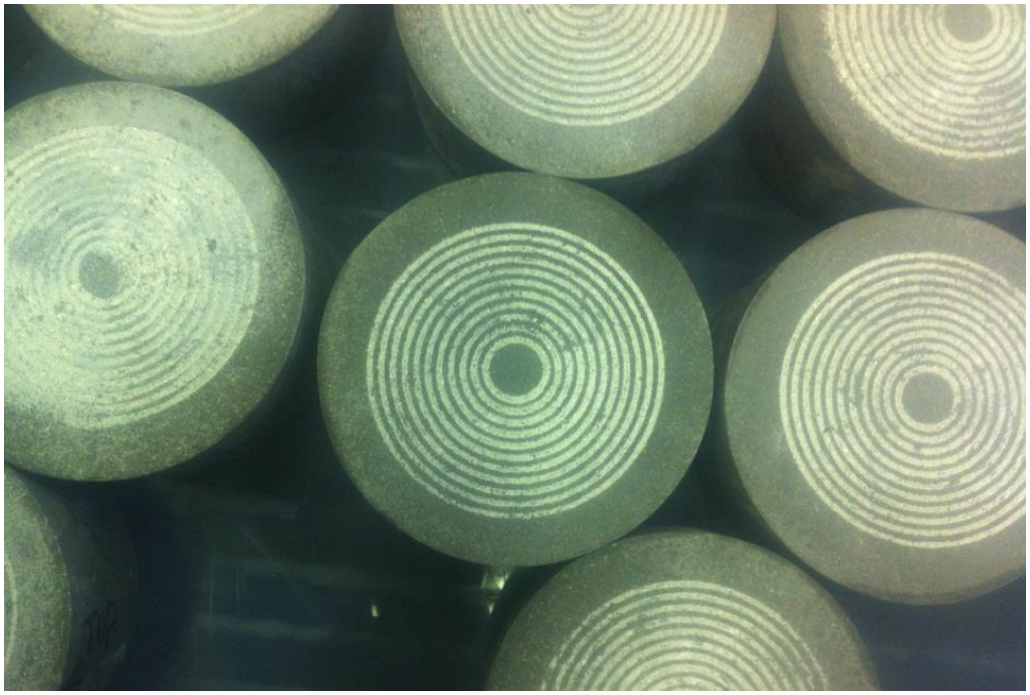


Figure 8.31: Concrete samples after the abrasion test (will be discarded after this test)

8.5.1.1.2.6 Activity of conducting a Imaging concrete

While the above tests were conducted in civil engineering research labs, the imaging tests were conducted at a different location. In the imaging test, the aim was to ascertain proper quality control; i.e., check whether the proper size and morphology of the nanosilica is present in the sample. In other words, in terms of research question, was the difference caused in the macroproperties actually a result of adding nanoparticles? Further, there was a necessity to ensure that the particle size of the nanosilica in the cement was less than 500 nm to qualify the material as bearing the prefix nano- (see Safiuddin, Gonzalez, Cao & Tighe, 2014). To gauge this issue, samples of cement with nanosilica were made. These samples were taken to a Transmission Electron Microscope (TEM) for detailed imaging study of the structure. While the civil engineers and I were present for the entire duration of the tests, a TEM operator conducted the actual imaging test. The operating cost of a TEM in a university setting was CAD$ 70. If nanoconcrete is to be used at a larger scale, then there will be a necessity for cheap imaging products and simple usable interfaces in the future.

8.5.2 Field Activities involved in civil engineering rersearch

Along with the lab research, civil engineers also test the materials in real-world conditions. Therefore, after the lab research, the next step was in considering nanoconcrete for real-world study. This required setting up proper baselines. Earlier, lab studies were conducted on noise absorption properties of nanoconcrete. There was a requirement for establishing baseline conditions for noise in the current real-world conditions of Ontario highways. Further, apart from the noise recording, the future steps in nanoconcrete research in this lab will be to use nanoconcrete as a material to be paved on part of a test track (few hundred meters) to allow for understanding the behavior of nanoconcrete in real-world conditions. Therefore, there was a necessity for establishing baseline conditions for the current state of the test track.

In the time I spent with the research group in pavement engineering, I had the chance to accompany them on three days of field research for data collection for establishing baselines. The first two days were spent at the test track and the last day was spent in data collection on a real highway. All the fieldwork was conducted on days in which the weather was clear and it hadn't rained for a few days, to ensure that the concrete was sufficiently dry.

8.5.2.1 Activities involved in conducting a Test Track Study

The research centre in Site 2, has a 1294 meters long and 8 meters wide L-shaped test track made of sections of various types of road-paving materials — asphalt & concrete along with various types of mixes, aggregates, polymer-mixes, and recycled materials, among others. It also has several sensors embedded for gauging stress and strain as well as weights, along with other instruments. The data can be gathered from these instruments from control panels located at the side of the test track. Since the test track is in open air conditions and also open to light traffic, the data from these instruments provide an understanding as to how the concrete matures and develops in relation to the weather changes in temperature as well as traffic.

As evident from the molding process, a unique aspect of concrete is that unlike other materials, it has to be carefully cured over a period of time before it is finally deemed ready. Further, due to its nature, longevity, and place of application, concrete continues to develop as a material. When used in pavements, concrete is affected not only by the weather but also the surrounding soil setup. Concrete matures slowly and develops with its surroundings. Thus, the test track serves as a valuable asset for pavement engineering research for understanding real-life conditions. In 2012, this particular test track had completed ten years of existence. In, the summer of 2013, a full forensic study of the test track was conducted. This forensic study involved coring out samples from the test track in order to run certain studies on them, such as, noise absorption tests, and friction tests, among others. The samples collected in this research study were to be a part of ongoing longitudinal study. The last time the samples were collected from this test track was about five years ago. To ensure that the cores were taken from the proper places, a whole day of analysis was conducted in which the proper places were marked from where the samples could be taken. In this analysis, the British Pendulum test and the Sand Patch test were conducted, in each section of the test track. Two samples, one from each lane, were taken from each section.

There were four members involved in this process. One member was marking the length from the beginning of each section. The next member was conducting the British Pendulum test, the third was involved in the Sand Patch test and the fourth was to serve as a helper in moving the stuff around. Since the fourth member of the group did not turn up, I filled in as the role of the helper. In this role, I had to move the pendulum around, set up the orange cones to segregate areas on the road while the researchers were conducting the tests. The tests were same as the one conducted in the lab. However, due to the road setup, at certain times the British pendulum had to be stabilized before taking the measurements. The researcher sat down next to the pendulum, while the other noted the readings. Then they switched places for the Sand Patch test. This turn taking continued for the entire test track. Having marked the points where the readings were taken for the research study, the data gathering was wrapped up for the day.

Figure 8.32: Test Track study

Figure 8.33: British Pendulum Test to be conducted on the asphalt and concrete roads

Figure 8.34: Sand patch test being conducted on asphalt road

Figure 8.35: Road being marked for coring

On another day, an external vendor was called to conduct the coring process. The places that were earlier marked served as the sites where the coring could take place. Coring involved using a portable cutter to cut out a section of the concrete. These holes were later filled up by the company. The work done on the test tracks, as well as civil engineering, requires a considerable amount of endurance. Overall, the research conducted on the test track and pavement setup has implications for roadways and hence for transportation research in Human Factors.

Figure 8.36: Coring of test track in progress

8.5.2.2 Activities involved in conducting a Noise Test on highway

Along with the test track study, another field research that I got involved in was studying noise levels in Ontario highways. The broader question that was to be asked was whether introduction of nanomaterials would decrease noise levels. Therefore, a background study was conducted to chart the noise levels in Ontario highways. In this study session, where I again acted as a helper, a set of microphones were attached to an external frame which was connected to one side of the vehicle. These microphones recorded the noise generated by the back tire, by means of a laptop connected to them.

Figure 8.37: Microphone setup being adjusted for noise study

The test involved driving on the three lanes of the highway at a fixed velocity for a short duration. In order to ascertain that proper readings would be taken, a few dynamic conditions were created. It was made sure that no other vehicle was quite close to the test vehicle while the readings were recorded. Therefore, first, a considerable distance was maintained between the vehicle before us and the test vehicle. Second, proper verbal coordination was required for data gathering process to run smoothly. Therefore, before the study, an informal coordination mechanism was decided upon for managing the experimental session. First a data gathering sheet was made prior to the beginning of the recording. During the session, I indicated the start and stop of each recording. Once the recordings of the first lane were completed, the researcher moved the vehicle to the next lane and indicated that I was to begin recording. In the next lane the same coordination process was repeated again. This informal coordination mechanism allowed for the easy flow of the experimental session.

This study, although seemingly straightforward, proved to be quite a challenge because of a few factors. The driver, even though having considerable expertise in driving, was new to Ontario highways. Further, driving and coordinating with the helper (me) about the experiment in real-time dynamic environment was a challenge. Imagine a freight truck roaring by in the next lane at a speed higher than 100 km/hr while a study is being conducted!

This noise study in real-time environments has implications for better design for highways and noise reduction. In terms of HFE research, introduction of nanomaterials will have an impact on the macroproperties of roadways and hence on the environment in terms of noise. There will be a necessity for proper design of roadways with the society in perspective; thus, presenting a viable research area for HFE in environmental design.

8.5.3 Generic Processes, Challenges and Ambiguities

This study was conducted in university civil engineering laboratory settings to understand the use of nanosilica in concrete. The ethnographic study was divided into two major phases—laboratory activities and field activities. The laboratory activities were further subdivided into two other subactivities pertaining to the making of samples and the testing of those samples. The activities of making the sample included mixing raw materials to produce wet concrete. Pouring wet concrete into the molds. The next step involves hardening the sample over a period of time and later demolding them. Finally, these samples were used for various tests for gathering research data. Along with activities conducted in the laboratory, the activities involved in the field consisted of data gathering in the test track and in the highways of Ontario. This work domain showed new challenges related to the body, workmanship and dexterity that were adequately comprehended with the two new hierarchies of acts and the person in WIDF (discussed in detail in the next chapter).

Over the course of this study, three important aspects were highlighted. First, nanoconcrete research in civil engineering can be labeled as situated activity, both during lab activities and field activities. In the lab, the activity of making involved creation of samples of concrete. This creation could be best described under the concept of “workmanship of certainty” (Pye, 1968). Workmanship of certainty involves less risk and a guarantee of successful outcomes. However, there is still some amount of ambiguity in the activity of making (creating and testing) the concrete sample. Along with the activity of making, ambiguity also occurs in general, in various instances in activities pertaining to nanoconcrete.

8.5.3.1 Nanoconcrete research as situated activity

A prominent theme that has emerged is the situated nature of activity in nanoconcrete settings. The situated nature of activity has received widespread acceptance in HFE based on various approaches from social scientists (Hutchins, 1995; Lave, 1988; Suchman, 2007). Particularly, situated activity can be understood as differentiated from plans. Typically, plans are prescribed as meaningful set of actions on which activities are constructed. However, in practice, activities are formed based on local contingencies. This view of local contingencies shaping the outcome is prominent in the concrete process as well as field-testing activities. In terms of the concrete-making process, actual activity emerges based on the different aspects of the situation; i.e. the materials, the workman and the interaction between the two. Further, extraneous aspects to the ongoing activity are also prominent. These extraneous aspects include cold damp air and humidity effects that constantly shape the end product. Therefore, concrete mixing in the lab, even though prominently displayed as planned steps, requires an examination in terms of emergence of various lines of action based on the circumstances. These lines of emergent activity includes the creation of concrete mix, pouring of concrete mix, making samples and demolding them. In case of field activities there was an initial plan that consisted of running a number of tests. However, the actual activity involved getting people together, resolving conflicting schedules, working outdoors in the hot sun, and gathering appropriate scientific data. Thus, the scientific data gathered involved the constraints of people engaged in activities in their surround.

Further, the creation of the concrete sample as situated activity showed how cognitive requirements should be understood along with physical capabilities of the researcher. A cognitive view of the concrete making process would only reveal the decisions and the intellectual steps to be taken for creating the concrete. However, dexterity played a crucial role in the creating of the concrete mix, molding the concrete, and demolding it. The entire process involved a bodily-based knowing that is not completely addressed by a cognitive understanding of the work domain. Therefore, even though the researchers had a cognitive understanding of the overall process, ingredients and the associated steps, the physical aspect of knowing provided a deep comprehension of the material. An example of this aspect is observed in the pouring of concrete mix into the molds. Along with the cognitive understanding of the scientific value and benchmarks obtained from the slump test, the researcher had a body-based understanding of the viscosity of the concrete mix and the way it should be poured into the mold so as to avoid air bubbles. Further, in order to ascertain that the concrete had settled properly, the concrete was poked with a stick so as to enable it to settle. At the same time, the poking should be such that it doesn't reach the bottom of the mold; the depth to which the stick has to be jabbed is determined by a physical knowing not completely comprehended by cognitive-understanding. Therefore, a body based understanding of situated knowing and acting was paramount in this work domain.

8.5.3.2 Making as activity; Ambiguity and the Workmanship of Certainty

Making concrete samples involved the "workmanship of certainty" (Pye, 1968). "Workmanship of certainty" indicates the generic process of making in which the outcome of concrete samples is predetermined and quality of the outcome is often ensured throughout the activity by particular checks. For example, there are several tests such as the slump test (described above). That led to the formation of concrete. The slump test ensures that the freshly formed concrete mix is usable for the project requirements. Thus, even though workmanship plays a crucial role in making the samples, having appropriate checks ensures a proper outcome. It is to be noted that even though the process is robust, it is not mechanistic and depends on the activities of the researchers. At times the concrete making process can be very fragile and filled with ambiguity at certain instances displaying the necessity of understanding the worker and his point-of-view. Specifically, to ensure proper outcomes, the dexterity, judgment and care of the maker (researcher) becomes necessary. For example, in the generic process of making the samples of concrete, the role of workmanship is prominent. Here the researcher in the capacity of workman ensures that the crafted product is in the form that is required for research. This crafted product is fairly certain in its outcome but still requires the role of the capabilities of the worker.

A similar aspect of workmanship of certainty is observed in the outcome of demolding, where the researcher uses a hammer and compressed air to demold the sample. However, even in this approach, the ambiguity and challenges arise due to the way in which sample is demolded. Various researchers use different strategies such as hitting the mold at various places along with other researchers who demold the samples by using the hammer as well as compressed air. These strategies require that the workman exercises judgment and care to ensure that the sample is not damaged. The ambiguity in these situations are small but at times may escalate to a broader level due to the researcher using excessive force to hammer the samples. Therefore, molding and demolding should be considered as subprocesses of the more generic process of making which in turn include other generic subprocesses. Taken together they emphasize that concrete research involves the generic process of making and related ambiguity involved in this process.

8.5.3.3 Role of ambiguity in activities pertaining to nanoconcrete

The work involving nanoconcrete was fairly straightforward; however it also consisted of various ambiguities during the conduct of activities. One of the challenges that the researchers faced was the outcome the concrete-mixing process. Typically, at the end of the process, the wet concrete parameters are tested by the slump test. Based on these results, the wet concrete material is either kept for molding or discarded. If the material is discarded, this means that there is loss of productivity and labor effort. This loss cannot be foreseen; thus, resulting in considerable ambiguity for the involved researchers. Similarly, in case of field activities involving noise testing, after setting up the apparatus and driving through the highway there was considerable ambiguity about the outcome of the data-gathering session. Therefore, immediately after the session, the gathered data was checked to ensure that the data was complete and no segments were missing. In case of missing segments, the data was gathered again for the given conditions. Therefore, field activities as well as lab activities consisted of considerable ambiguity during the progress of activity. However, these activities were solved in a short term when researchers revisited the outcomes and chose other lines of approach. Therefore, while considerable ambiguity remained, researchers effectively handled these in the short term to reach successful outcomes. In other words, in the site as a whole, the ambiguity was nullified and did not present the same amount of risk as in other sites (c.f. this thesis, site1 on LOC devices).

8.5.4 Conclusion

This study provided an insight into how nanotechnology was used in civil engineering research. A crucial insight gained from this study was that nanotechnology loses its identity in the disciplinary matrix of civil engineering. Therefore, the civil engineers were using nanotechnology for their own ends rather than doing nanotechnology research *per se*. However, nanomaterials hold a widespread promise for civil engineering. In the subfield of pavement engineering, where nanotechnology was used, the research activities included making concrete samples using nanosilica and testing these samples with various tests such as the Compression test, Sound Absorption test, British Pendulum test, Sand Patch Test, Abrasion Test and Imaging techniques. These tests were conducted to ascertain that the addition of nanoparticles had a relevant effect on the macroscopic properties of the concrete. Along with these lab activities of mold making and testing, field activities in pavement engineering involved collecting data from a test track to understand the change in the properties of concrete due to weathering, as well as collecting data for a study of noise in highways. This current chapter served as the first step for WIDF and identified the crucial dimensions of the body, workmanship and associated activities. These will be developed in detail in terms of engineering models. In the next step the engineering models are presented in detail and compared with those of CWA.

Chapter 9: Site 3—Engineering Analysis for Nanomaterials

9.1 Introduction

In the chapter 8, the first step of WIDF for nanoconcrete was presented. This step consisted of an ethnography conducted in a concrete laboratory that was using nanomaterials for design of next generation concrete pavements. In this current chapter, the second step of WIDF, which provides the design requirements, is presented. Along with presenting this second step, this chapter also compares the design requirements derived from both WIDF and CWA. In developing the CWA approach, three texts (Vicente, 1999; Bisantz & Burns, 2009; Burns & Hajdukewicz, 2004) and two documents (Kilgore, St-Cyr & Jamieson, 2009; Miller & Vicente, 2001) were used as foundations for developing the CWA based analysis. The structure of the rest of the chapter is as follows. First, the system formulation is presented. Next based on the system formulation, two phases pertaining to the work domain are identified. In this present domain, the samples of nanoconcrete are made in the concrete lab and then they are tested. The making and testing of concrete are presented as two separate phases; both of these involve analysis related to CWA as well as WIDF. At the end of each phase, the requirements derived from the two sets are compared to each other.

9.2 System Formulation

The scope of the earlier chapter 9a was to understand the creation of nanoconcrete samples for testing in a research laboratory. It was highlighted that the concrete samples were created in the concrete laboratory. After a period of seven or twenty-eight days, depending on the requirements of the project, these samples were tested. In general, to address the salient aspects of the system under consideration, two main phases were considered – nanoconcrete making phase and the testing phase. In the nanoconcrete-making phase, the system is demarcated in order to account for all the entities related to the actual creation of the nanoconcrete samples from scratch. In contrast, the testing phase consisted of different tests to ascertain the properties of concrete such as durability, friction-related properties, among others. At the testing phase many different tests were used, the system was modeled at a broader level. In other words, a coarse grained view of the system was taken at the level of multiple tests, rather than providing a fine-grained analysis of the individual tests. Finally, for each of the two phases, models pertaining to both WIDF and CWA were created and the design requirements gleaned from them were compared to each other.

9.3 Phase 1—Creating nanoconcrete samples

9.3.1 CWA

9.3.1.1 WDA

The first step in CWA is the work domain analysis. The following figure (AH 1.0, Figure 9.1) presents the abstraction hierarchy related to creation of nanoconcrete samples. At the level of the functional purpose, there is one major purpose related to the creation of the proper concrete samples based on project requirements. At the next level of abstract function, there is the conservation of mass based on stoichiometric relations. This is due to the chemical reactions that enable the concrete to be created from its various constituents of aggregates and materials.

At the level of generalized function, two main categories of processes exist. First, there is the creation of concrete by the chemical processes (hydration). Second, there are physical processes related to the creation of the concrete samples and demolding them. Both these processes will be discussed in detail in the causal representation of the abstraction hierarchy. The processes involved in the level of generalized function requires many materials and their related properties. Thus, at the level of physical function, these various entities are highlighted. These entities include coarse aggregate, fine aggregate, cement, among others (see AH 1.0). For example, as discussed in chapter 9a, Portland cement is used along with water and other aggregates for the hydration process for creating the concrete. Finally, at the level of physical form, various characteristics of the above entities are described at the level of physical form. For example, at this level of physical form, coarse aggregate should have a diameter between 0.375 to 1.5 inches.

Other descriptions include particles, liquid, among others (depending on the entities involved in the work domain).

Along with the description of AH 1.0, a causal representation is also present (AH 1.1, Figure 9.2). In this causal representation, the abstract function level and the generalized function level are developed in detail. At the abstract function level, there is a conservation of mass based on stoichiometric relations. Therefore, the initial mass of materials (e.g. cement, aggregates etc.) are also involved in chemical reactions that leads to the formation of chemical compounds. These compounds, along with the entire mixture, react to form fresh concrete and releases heat. Next to the level of abstract function, the level of generalized function constitutes two major categories of processes related to the chemical processes in the formation of fresh concrete and the creation of samples from the fresh concrete.

After the chemical process of hydration, fresh concrete is produced. The fresh concrete is in dotted lines because it is not a process but an intermediate product between the processes. This fresh concrete is first used for filling the molds, and then using a trowel the surface of the concrete is provided a plain finish. After the surface finish, the concrete is left to harden for twenty–four hours. After this time period, the concrete sample is removed from its mold. Once demolded, the concrete samples are placed in a humidity chamber for curing. The curing time can either be seven or twenty-eight days depending on the project requirements. In this phase, of creating the concrete samples, the whole system is considered as a single unit with an output in terms of concrete samples. Therefore, at this phase, there is no subdivision of the system in terms of subsystem and therefore; thus, the abstraction decomposition space has not been developed of this space.

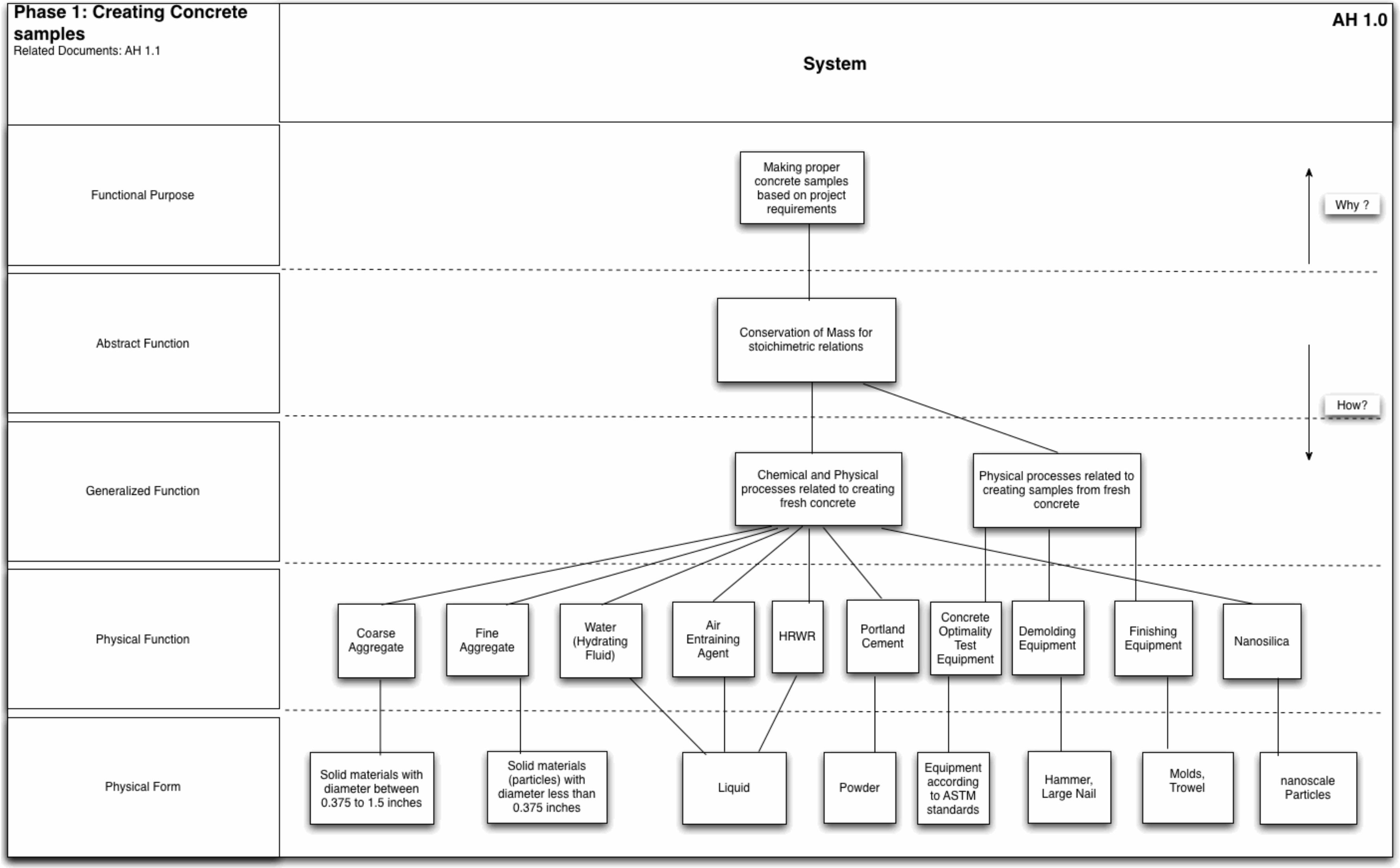


Figure 9.1: Abstraction hierarchy, AH 1.0, creating concrete samples for phase 1

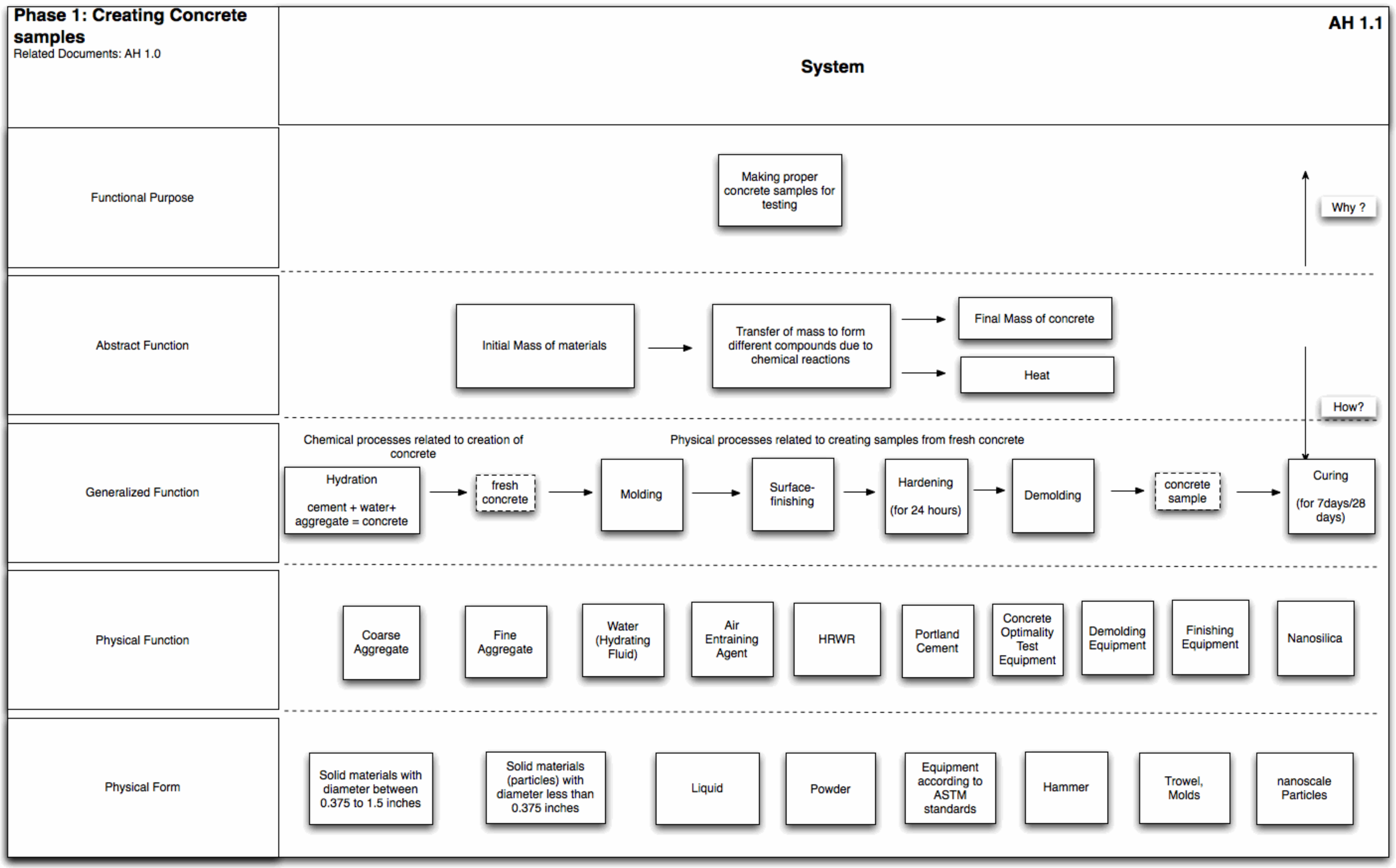


Figure 9.2: Causal Representation of the abstraction hierarchy, AH 1.1, for phase 1 of creating concrete samples

9.3.1.2 ConTA

The second step of the WDA is the control task analysis. In this analysis, the main aim is to identify what needs to be done in order to achieve the functional purpose of the domain. In the present case, the detailed steps for the control task of creating the nanoconcrete samples are presented (DL 1.0, Figure 9.3).

Control task analysis of making the concrete samples -Decision Ladder **ConTA 1.0**
Related documents: AH 1.0

Number	**Ladder Code**	**Notes**	**Type**	**Abstraction Level**
1	Goal state	The number of concrete samples to be made in one batch is identified. Accordingly, the weight of materials is planned	Knowledge State	Functional Purpose, Abstract Function
2	Define Task	The associated tasks, such as gathering the aggregates, mixing the aggregates etc., are defined.	Information Processing Activity	Generalized function, Physical function
3	Task	Tasks are formulated based on the various activities involved in making the concrete samples	Knowledge State	Generalized function, Physical function
4	Formulate procedures	A task state is formulated based on the number of tasks and the order in which they are executed	Information Processing Activity	Physical Function
5	Procedure	A procedural state is formed that encapsulates the procedures formulated in the previous states as well as the order in which they have to be executed. For example, first step is to mix the materials in the rotary mixer to enable hydration process. Second, check the concrete based on the slump test. Third, pour concrete into the molds. Fourth, demold the concrete after 24 hours. Fifth, cure the concrete for 7/28 days	Knowledge State	Physical Function, Physical Form

6	Execute	The planned procedures are executed beginning from the mixing of the various weighed components in a rotary mixer	Activity	Physical Form
7	Identify	Information about the state of the outcome of the procedure is identified. For e.g. after the fresh concrete is prepared, administer the slump test and identify the state of the fresh concrete	Information Processing Activity	Generalized Function, Abstract Function, Physical Function
8	System State	Based on the results of the concrete making steps, the overall system state is comprehended.	Knowledge State	Generalized Function, Abstract Function, Physical Function
9	Task	Based on the overall system state the task state following the one just completed is selected and those tasks are progressed on with.	Knowledge State	Generalized Function, Physical Function, Physical Form

Table 9.1: Control Task analysis for making concrete in phase 1

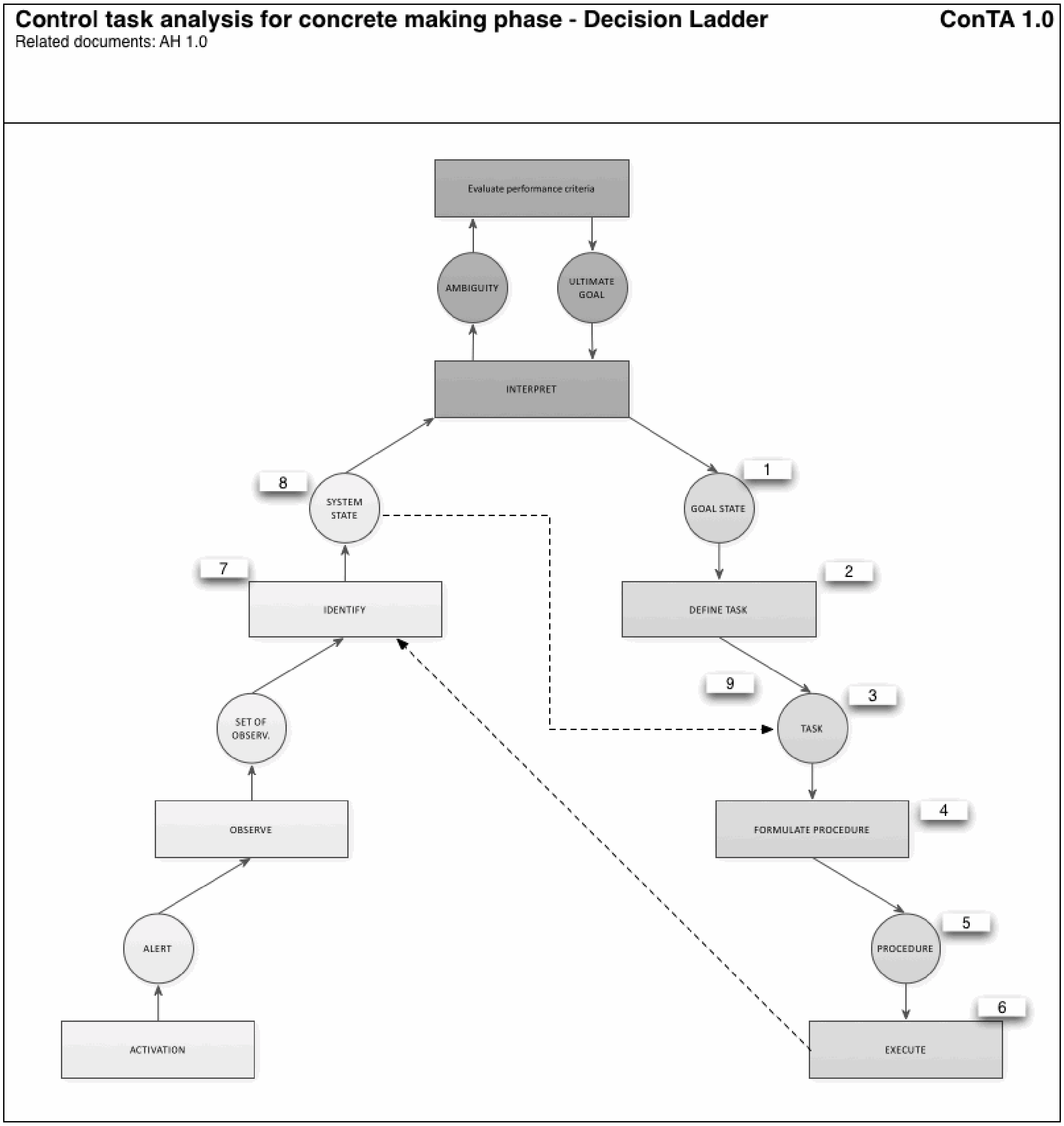


Figure 9.3: Concrete task analysis for Phase 1 for creating concrete samples

9.3.1.3 StrA

After the Control task analysis, a strategies analysis is conducted to understand, how the tasks are accomplished to achieve the functional goals of the system for the fabrication phase. The making of nanoconcrete samples is done by a standard procedure based on industrial guidelines. Therefore, the individuals involved in the process have less freedom for developing their own strategies for concrete mixing process. However, the typical strategies associated with this phase are salient in case of demolding the samples. Below, this main strategy is discussed in detail (StrA 1.1, Figure 9.4)

Strategies analysis for demolding the concrete samples **StrA 1.1** Related documents: AH 1.0, DL 1.0	
1	The first strategy for demolding involves taking a mold (with the hardened sample still in it) and inverting it. Then a chisel is placed at the bottom center of the mold and hit gently using a hammer. Then the mold is rapped on the sides gently with the hammer in order to loosen it. Finally, compressed air is passed through the narrow space between the sample and the mold; thus, loosening the mold. This strategy was generally adopted by researchers who were more experienced. For example, one researcher adopting this strategy had research experience both in university and industrial settings, related to working with concrete materials. This particular strategy of demolding allowed for introducing lesser amounts of stresses and strains on the molds as compared to the second strategy of hitting the molds randomly.
2	A second strategy for demolding involves taking a hammer and hitting the sides of the mold randomly. Then the mold is upturned and the bottom is hit randomly. In many cases, this loosens the sample. However, in case the sample hasn’t loosened, the sides of the molds are hit again at random places until it is finally loose. This strategy was generally adopted by less experienced researchers. This particular strategy also increased the likelihood of introducing more amounts of stress and strains on the molds, before the actual testing.

Table 9.2: Strategies analysis for demolding the concrete samples

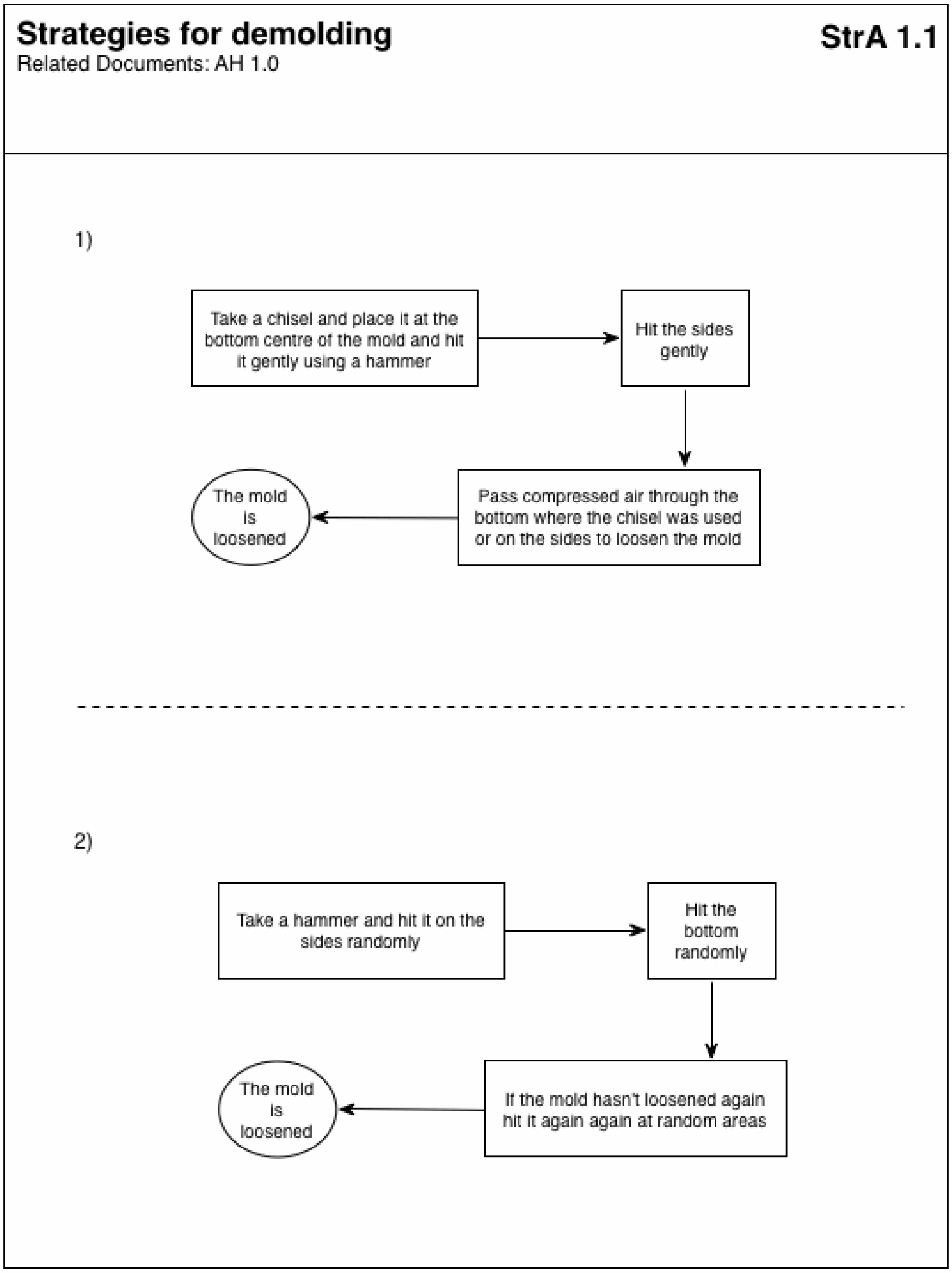


Figure 9.4: Strategies for demolding the concrete samples in phase 1

9.3.1.4 WCA

The last phase of analysis for CWA consists of the worker competency analysis. In this phase, the competencies required for the workers involved, are addressed in terms of skills, rules and knowledge required for the work domain. The following figure (SRK 1.0, Table 9.3) represents the constraints related to skills, rules, and knowledge categories for every information processing step and associated knowledge state.

Worker competencies analysis of making concrete samples Related documents: AH 1.0				**WCA 1.0**
Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge- Based Behavior**
Associated Number	**Associated Number**			
	Goal state			Reasoning required to identify the number of concrete samples, weight of samples, etc. based on project requirement
	1			
Define Task	Task		Rules and heuristics required for each task of making concrete samples	Reasoning required for formulating the tasks associated with concrete making from the various materials along with the making the sample for testing
2	3			
Formulate procedures	Procedures	Perceptual-haptic knowledge required for each step of the overall process. E.g., perceptual-haptic skill required in conducting slump test	Heuristics and rules for conducting the steps of the process based on the standards and protocol put forward by regulatory association such as concrete	Knowledge about the background of the standards and activities required for the concrete making. The details of the procedures are formulated based on the materials and the requirements of the regulatory bodies associated with the manufacture of

4	5		associations	concrete (for e.g., American Society for Testing and Materials, ASTM).
Execute		Perceptual-haptic skill required for orchestrating the entire activity of making concrete, pouring them into molds, and demolding of the final samples.	Heuristics involved in each step of the concrete making process. For e.g., during mold making, the concrete is packed properly to remove air bubbles. This requires using a rod to puncture the concrete in a manner so that the rod does not hit the bottom of the mold. Otherwise the concrete will not form an even layer at the bottom.	Background theoretical knowledge required for understanding how the concrete is formed. This includes, chemical properties, chemical reactions, and stages in the concrete making process, etc.
6				
Identify	System State	Perceptual skills required to identify the results of tasks, so that the next tasks can be continued. For e.g., the results of the slump test have to be identified in order to		Disciplinary knowledge of tests such as the slump test, air entrainment test, etc. are required to identify the state of the concrete and continue with the sample making process
7	8			

		continue the molding		
Define Task				Based on the identification of the system state, the next task is formulated. For e.g. in many cases, the results of the slump test may show that the concrete is not properly formed. As a result, that batch of concrete can be discarded, or alternatively could be retained by adding other materials in the mixture according to the specifications
9	10			

Table 9.3: Worker competency analysis outlining the skills, rules and knowledge required for the concrete making process

9.3.2 WIDF

9.3.2.1 RCH Environment

Beginning with the RC hierarchy related to the environment, the functional purpose consists of proper concrete samples, based on the project requirements. At the level of the abstract functions, there is a conservation of mass for stoichiometric relations. The conservation of mass is explained in detail in the causal representation of RCH environment (RCH 1.1, Figure 9.5). At the next level of generalized function, there are two main sets of processes. The first set is related to the creation of fresh concrete while the second set constitutes physical processes related to the creation of samples from fresh concrete. These two processes will be explained in detail in causal representation of RCH environment (RCH 1.1.1).

The processes at the level of generalized function are instantiated by entities at the level of physical function in terms of their capabilities. These entities include coarse aggregate, fine aggregate, Portland cement, among others. Their capabilities are involved in consideration of the overall functioning of the work domain. The next level of physical form considers the physical characteristics of the entities of the previous levels, for the overall functioning of the work domain. Examples of the entities at the physical form level include description of coarse aggregates as solid materials with diameter between 0.375 to 1.5 inches. Similarly, fine aggregate consists of solid material of diameter less than 0.375 inches. Also, other characteristics are provided in terms of descriptions such as solid, liquid, powder, among others. Along with the level of physical form, the level of use values (affordances) describes the properties of the entities of the system apart from what is intended for the system's correct functioning. These properties of the entities in this particular domain can be delineated in terms of properties that take into account the change in the workability of materials. Thus along with the changes provided in terms of the chemical reactions, the different materials allow for certain manipulations conducted on them in the course of the production of concrete. Therefore, workability of materials is a property that comes to the forefront while producing the concrete. Further, in case of powdered nanoscale particles, along with the function they have in the overall system for phase 1, they also pose a hazard for eyes and respiration.

Along with the representation of the environment in terms of RC hierarchy, there is also a representation in terms of causal processes (RCH 1.1.1, Figure 9.6). In the representation RCH 1.1.1, two main levels are addressed in detail – level of abstract function and the level of generalized function. At the level of abstract function, the conservation of mass can be explicated by considering the initial mass of materials. This mass is transferred into different compounds due to chemical reactions, such as hydration. Thus, resulting in a final mass of concrete and the release of heat. At the next level of generalized function, two main sets of processes relating to the creation of concrete and physical processes relating to the creation of samples become prominent. Therefore, in terms of creation of concrete, there is the process of hydration that involves cement, water and aggregate to produce concrete. The fresh concrete (shown in dashed lines, as it is an intermediate product), is used for molding. After molding, the process of surface finishing is used for making the top surface parallel to the bottom surface. The concrete is left to harden or solidify over the course of the next twenty-four hours. Once this duration is completed, by the process of demolding the concrete samples are separated from the mold. After separation from the mold, the concrete is left in the humidity chamber for curing, for a duration depending on the time requirements of the project (seven or twenty-eight days). After considering the causal representation, typically the abstraction-decomposition space is constructed. However, in this case of concrete sample creation, there is no clear-cut demarcation between the system and its subsystems. Therefore, the abstraction-decomposition space is not considered for this phase of making concrete samples. The abstraction-decomposition space is developed in detail for phase 2 related to testing.

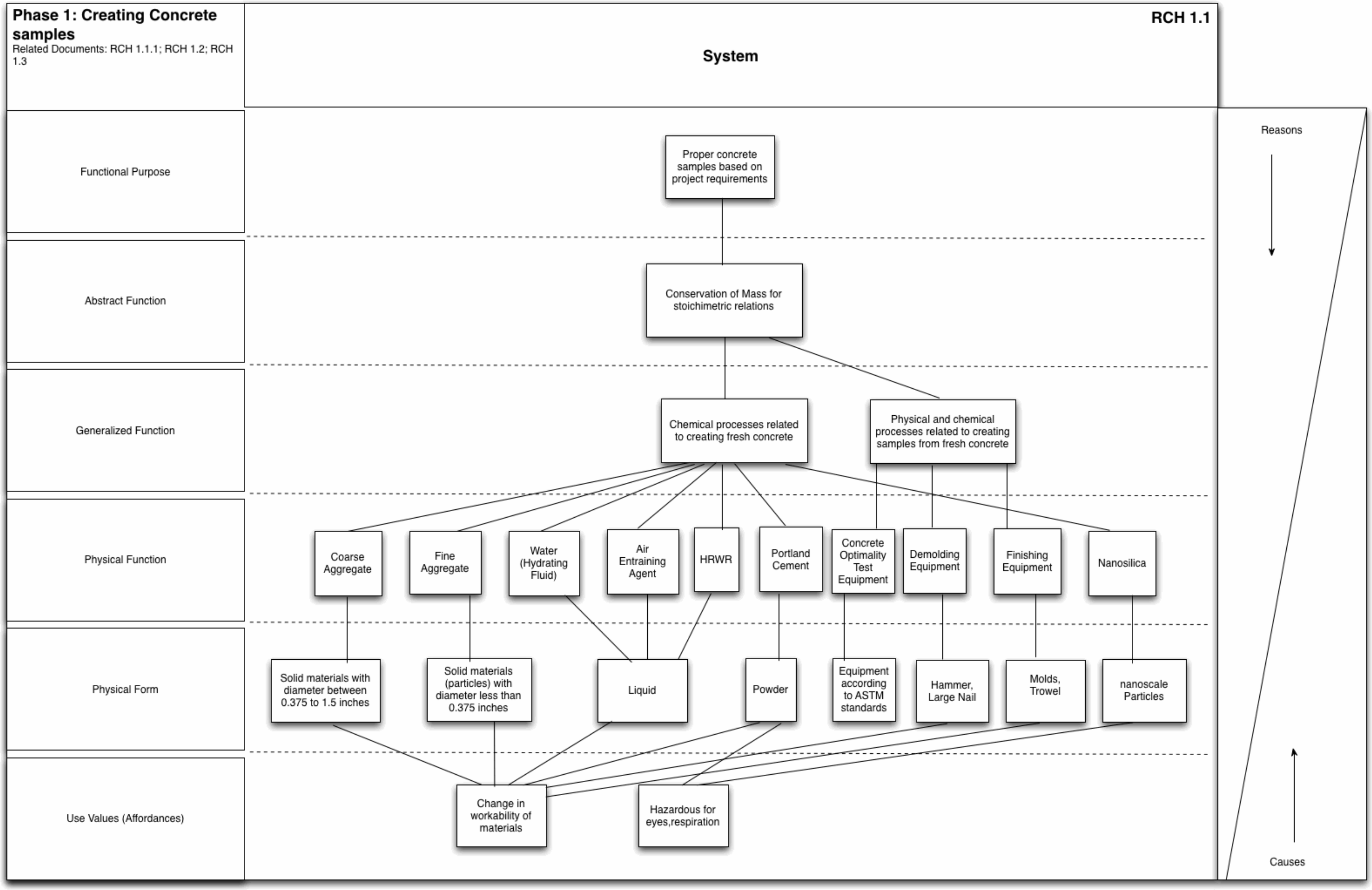


Figure 9.5: RCH Environment for Phase 1 creating the concrete samples

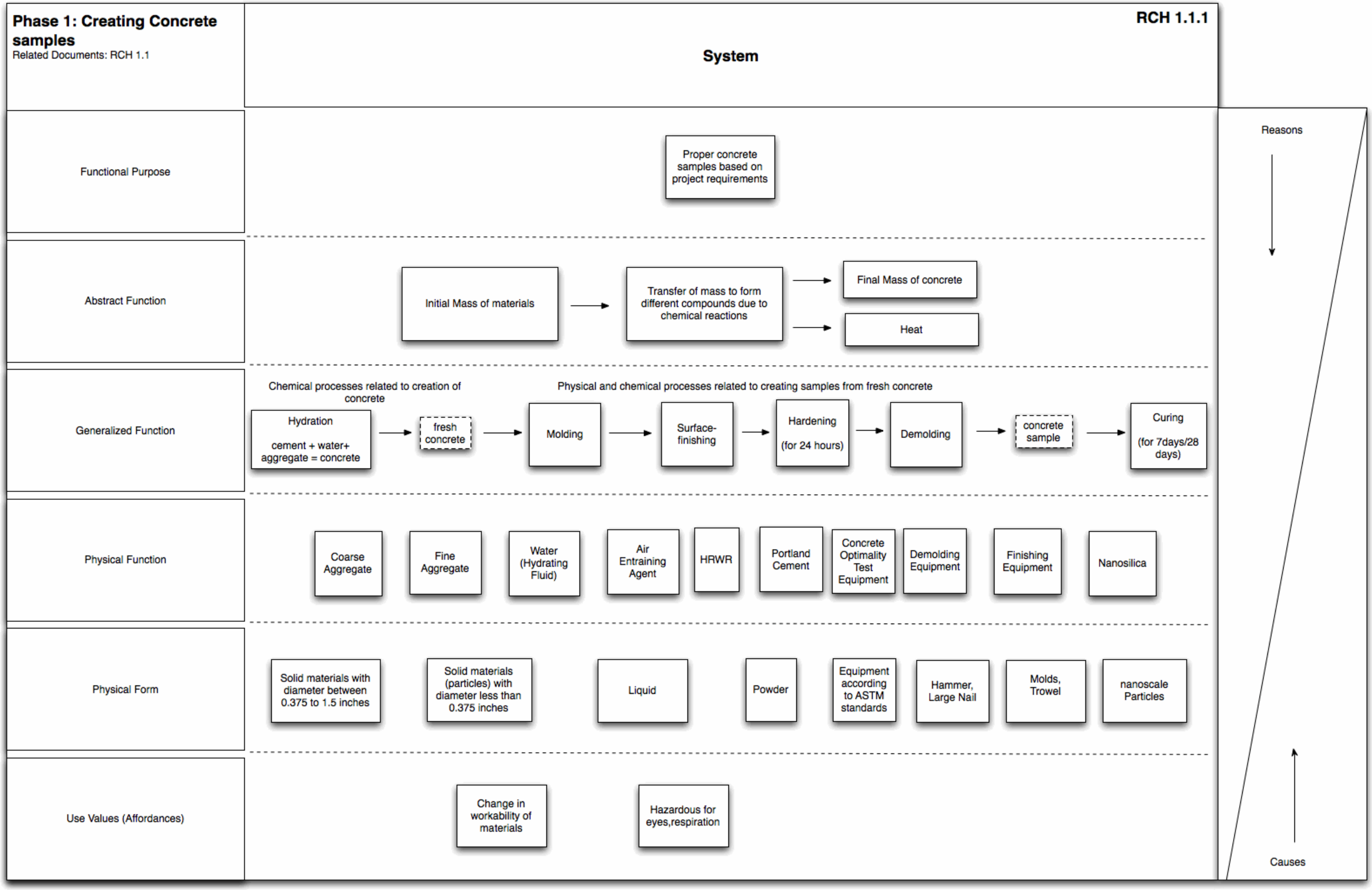


Figure 9.6: Causal representation of RCH Environment for creating concrete samples

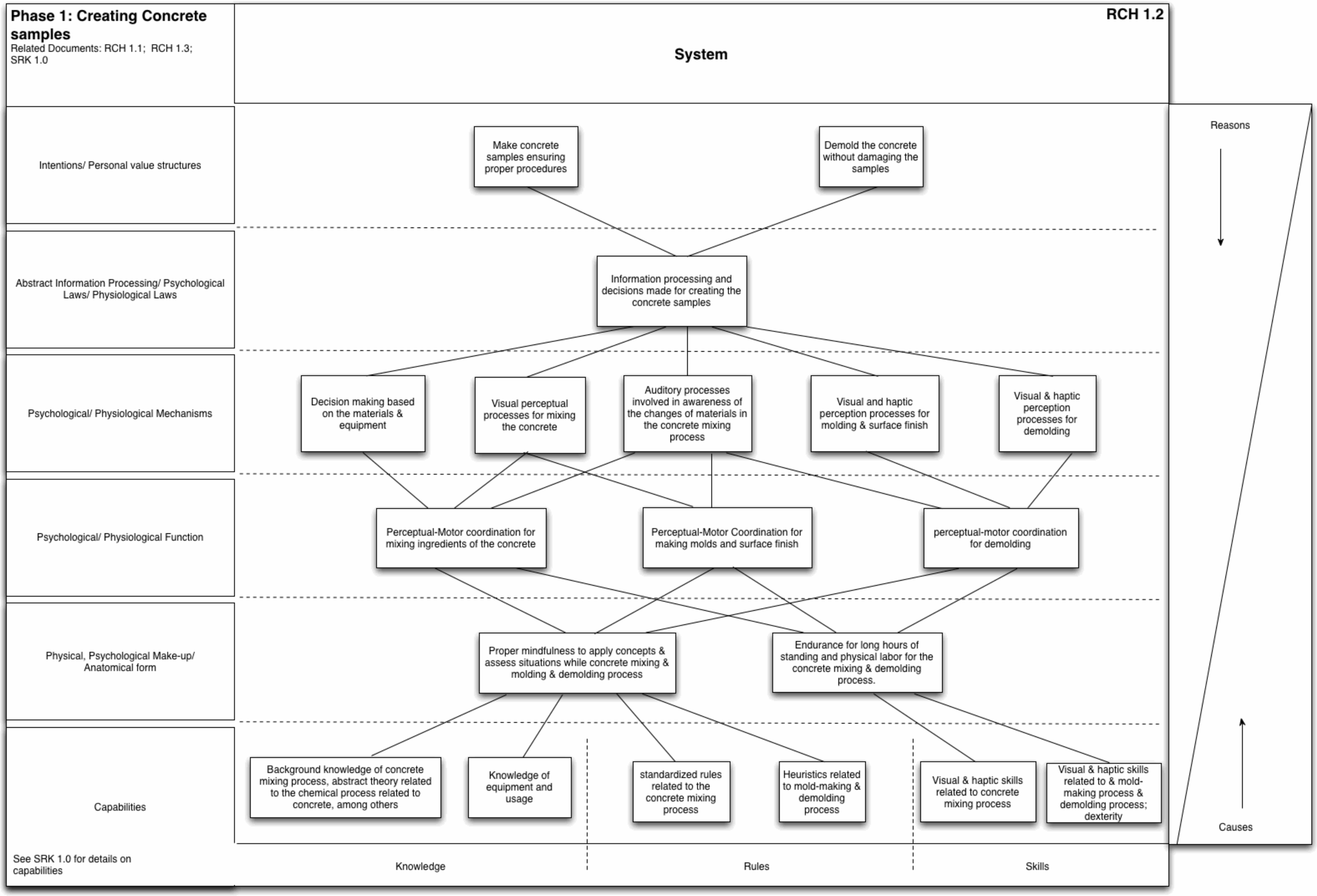


Figure 9.7: RCH Agent for Phase 1 of creating the concrete samples

9.3.2.2 RCH Agent

Along with the RC hierarchy for scene, the next hierarchy for consideration is the RC hierarchy for agent (RCH 1.2, Figure 9.7). In this hierarchy, at the first level of intentions, two main aspects are to be considered. First, making concrete samples to ensure proper procedures. Second, demolding concrete samples in a manner so as not to damage them. At the next level of information processing, there is the abstract representation of the information processes and decisions to be made for creating the samples. Next, at the third level related to psychological and physiological mechanisms, there are processes related to decision making for ascertaining the weight of materials, number and size of samples, among other requirements, based on the research project. Further, there are many perceptual processes involved in concrete making. These include, processes related to vision required for the concrete mixing; auditory processes are also involved in the awareness of the changes in materials in the concrete mixing process; visual and haptic processes are involved for molding and surface finishing of the samples; along with haptic processes are involved in the process of demolding.

At the next level related to psychological/physiological function, there is perceptual-motor coordination required for different processes; such as, perceptual-motor coordination for mixing the ingredients of the concrete; perceptual-motor coordination for making the molds and surface-finishing the molds; along with the perceptual-motor coordination is required for demolding. At the next level pertaining to physical, psychological make-up, there is the necessity for proper mindfulness to apply concepts and assess situations while the concrete mixing, molding and demolding processes are underway. Further, endurance for long hours of standing and physical labor is required for the concrete mixing and demolding process. The final level of the RCH for agent includes a description of the skills, rules and knowledge required for the work domain under consideration. Therefore, in terms of skill, there is dexterity needed for the molding and demolding processes. Further, visual and haptic skills are required for the concrete making process in its entirety. Along with the background disciplinary knowledge there is a knowledge required for understanding equipment and its usage in the work domain. . The layer of capabilities is developed in further detail in terms of the SRK taxonomy (SRK 1.0, Table 9.4). Further since there are only one kind of agent, i.e., nanoconcrete researchers, involved in a set of activities, the abstraction decomposition space has not been developed for RCH Agent and Acts for Phase 1 or Phase 2.

Skills, Rules and knowledge required for making concrete samples **SRK 1.0**
Related documents: RCH 1.0

Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge- Based Behavior**
Associated Number	**Associated Number**			
	Goal state			Reasoning required to identify the number of concrete samples, weight of samples, etc. based on project requirement
	1			
Define Task	Task		Rules and heuristics required for each task of making concrete samples	Reasoning required for formulating the tasks associated with concrete making from the various materials along with the making the sample for testing
2	3			
Formulate procedures	Procedures	Perceptual-haptic knowledge required for each step of the overall process. E.g., perceptual-haptic skill required in conducting slump test	Heuristics and rules for conducting the steps of the process based on the standards and protocol put forward by regulatory association such as concrete associations	Knowledge about the background of the standards and activities required for the concrete making. The details of the procedures are formulated based on the materials and the requirements of the regulatory bodies associated with the manufacture of concrete (for e.g., American Society for Testing and Materials, ASTM).
4	5			

Execute		Perceptual-haptic skill required for orchestrating the entire activity of making concrete, pouring them into molds, and demolding of the final samples.	Heuristics involved in each step of the concrete making process. For e.g., during mold making, the concrete is packed properly to remove air bubbles. This requires using a rod to puncture the concrete in a manner so that the rod does not hit the bottom of the mold. Otherwise the concrete will not form an even layer at the bottom.	Background theoretical knowledge required for understanding how the concrete is formed. This includes, chemical properties, chemical reactions, and stages in the concrete making process, etc.
6				
Identify	System State	Perceptual skills required to identify the results of tasks, so that the next tasks can be continued. For e.g., the results of the slump test have to be identified in order to continue the molding		Disciplinary knowledge of tests such as the slump test, air entrainment test, etc. are required to identify the state of the concrete and continue with the sample making process
7	8			

Define Task				Based on the identification of the system state, the next task is formulated. For e.g. in many cases, the results of the slump test may show that the concrete is not properly formed. As a result, that batch of concrete can be discarded, or alternatively could be retained by adding other materials in the mixture according to the specifications
9	10			

Table 9.4: Skills, Rules and Knowledge Taxonomy for the capabilities of RCH Agent

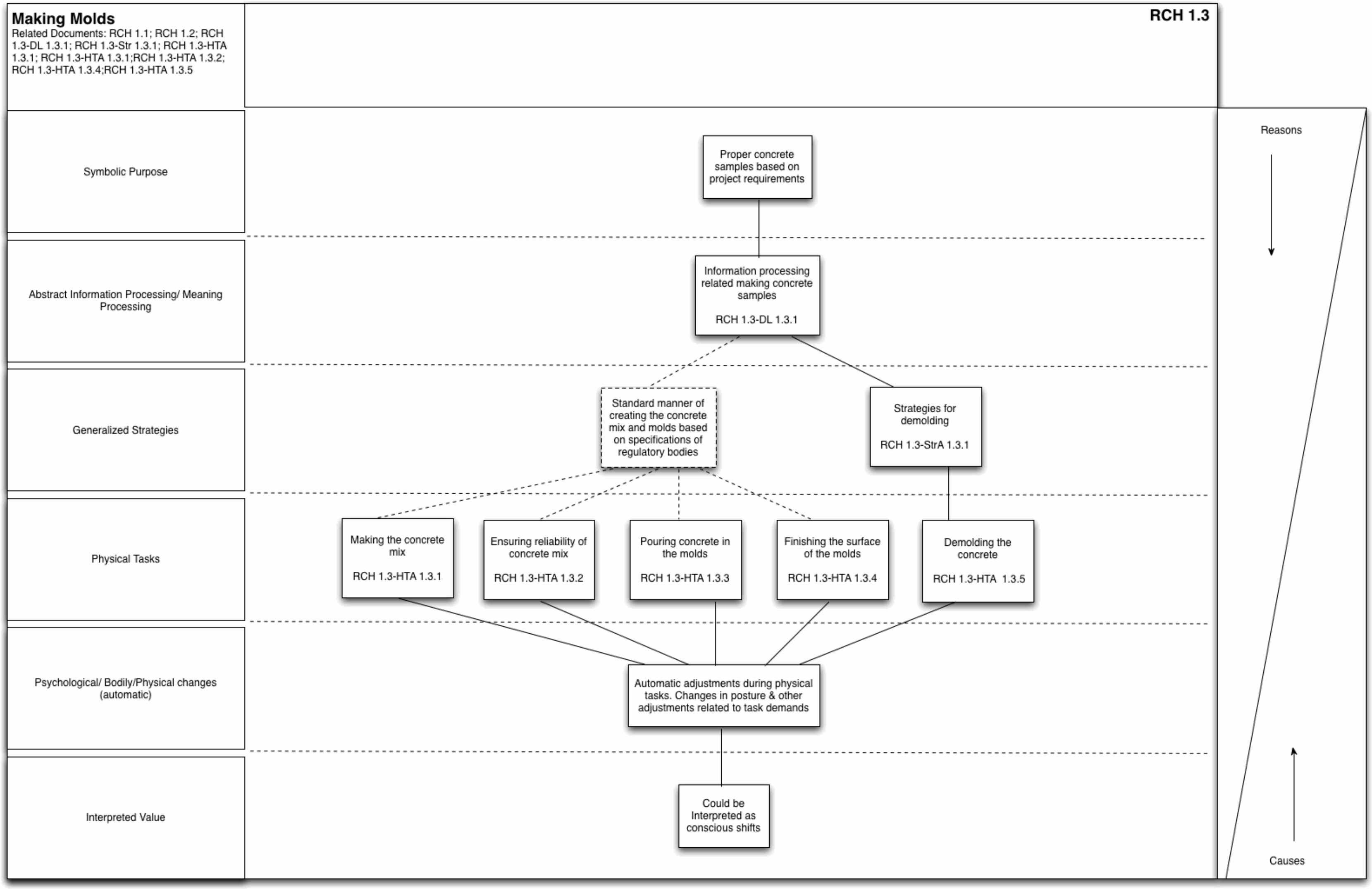


Figure 9.8: RCH Act for phase 1 of making concrete samples

9.3.2.3 RCH Act

Along with the two hierarchies pertaining to the environment and the agent, the third hierarchy consists of acts (Figure 9.8). In this hierarchy, the first level of symbolic purpose consists of one entity emphasizing the purpose of having concrete samples based on project requirements. At the second level of abstract information processing/meaning processing, the information processing activities related to making concrete samples are described. This entity is developed further in the form of decision ladder (RCH 1.3-DL 1.3.1, Figure 9.9).

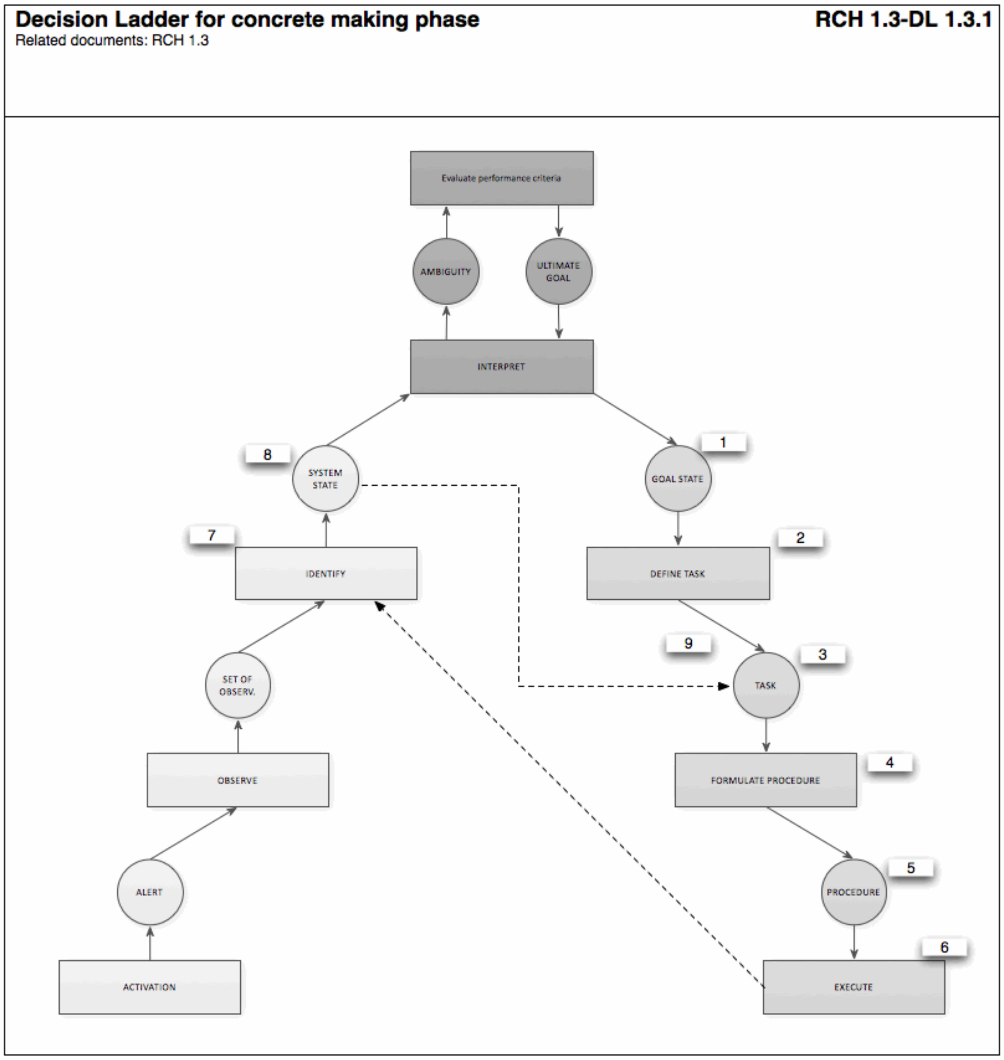


Figure 9.9: Decision ladder associated with the information processing activities for the concrete making phase

Information processing activities for making the concrete samples -Decision Ladder **RCH 1.3-DL 1.3.1**

Related documents: RCH 1.0

Number	Ladder Code	Notes	Type	Abstraction Level
1	Goal state	The number of concrete samples to be made in one batch is identified. Accordingly, the weight of materials is planned	Knowledge State	Functional Purpose, Abstract Function
2	Define Task	The associated tasks, such as gathering the aggregates, mixing the aggregates etc., are defined.	Information Processing Activity	Generalized function, Physical function
3	Task	Tasks are formulated based on the various activities involved in making the concrete samples	Knowledge State	Generalized function, Physical function
4	Formulate procedures	A task state is formulated based on the number of tasks and the order in which they are executed	Information Processing Activity	Physical Function
5	Procedure	A procedural state is formed that encapsulates the procedures formulated in the previous states as well as the order in which they have to be executed. For example, first step is to mix the materials in the rotary mixer to enable hydration process. Second, check the concrete based on the slump test. Third, pour concrete into the molds. Fourth, demold the concrete after 24 hours. Fifth, cure the concrete for 7/28 days	Knowledge State	Physical Function, Physical Form
6	Execute	The planned procedures are executed beginning from the mixing of the various weighed components in a rotary mixer	Activity	Physical Form
7	Identify	Information about the state of the outcome of the procedure is identified. For	Information Processing	Generalized Function, Abstract

		e.g. after the fresh concrete is prepared, administer the slump test and identify the state of the fresh concrete	Activity	Function, Physical Function
8	System State	Based on the results of the concrete making steps, the overall system state is comprehended.	Knowledge State	Generalized Function, Abstract Function, Physical Function
9	Task	Based on the overall system state the task state following the one just completed is selected and those tasks are progressed on with.	Knowledge State	Generalized Function, Physical Function, Physical Form

Table 9.5: Information processing activities for making concrete samples

The third level represents generalized strategies. Typically, this layer represents more than one strategy. However, as described in chapter 8a, the present work domain is highly constrained. The concrete making process typically follows standard procedures. Therefore, researchers have less leeway in the manner in which they consider their activities. Subsequently, in this particular domain, the strategies that researchers employ during demolding become prominent. In RCH 1.3 two entities are represented. First, in accordance to the requirements of this level, the strategies for demolding are presented (RCH 1.3-StrA 1.3.1, Figure 9.10). Second, in order to preserve continuity with the level above and the level below, the standard manner of creating the concrete mix is presented. However, since this entity is not strictly a set of strategies employed, it is represented as dashed lines.

After the level of generalized strategies, the physical tasks are presented. At this level five major entities are present—tasks for making the concrete mix (RCH 1.3-HTA 1.3, Figure 9.11); tasks for ensuring reliability of concrete mix (RCH 1.3-HTA 1.3.1, Figure 9.12); tasks related to pouring concrete in the molds (RCH 1.3-HTA 1.3.3; Figure 9.13); tasks related to surface finishing the molds (RCH 1.3-HTA 1.3.4, Figure 9.14) and finally, tasks related to demolding the concrete (RCH 1.3-HTA 1.3.5, Figure 9.15). Each of these tasks has been developed in terms of hierarchical task analysis. At the next level of psychological/bodily or physical changes, automatic adjustments are made during physical tasks are represented. These automatic changes may be due to changes in posture and other adjustments related to task demands. These automatic changes could be interpreted as conscious shifts and are categorized in the layer of interpreted value. After completing the description of RCH Act, finally, this phase concludes with a comparison between CWA and WIDF for Phase 1 (Table 9.7).

Strategies analysis for demolding the concrete samples **RCH 1.3-StrA 1.1** Related documents: AH 1.3	
1	The first strategy for demolding involves taking a mold (with the hardened sample still in it) and inverting it. Then a chisel is placed at the bottom center of the mold and hit gently using a hammer. Then the mold is rapped on the sides gently with the hammer in order to loosen it. Finally, compressed air is passed through the narrow space between the sample and the mold; thus, loosening the mold. This strategy was generally adopted by researchers who were more experienced. For example, one researcher adopting this strategy had research experience both in university and industrial settings, related to working with concrete materials. This particular strategy of demolding allowed for introducing lesser amounts of stresses and strains on the molds as compared to the second strategy of hitting the molds randomly.
2	A second strategy for demolding involves taking a hammer and hitting the sides of the mold randomly. Then the mold is upturned and the bottom is hit randomly. In many cases, this loosens the sample. However, in case the sample hasn't loosened, the sides of the molds are hit again at random places until it is finally loose. This strategy was generally adopted by less experienced researchers. This particular strategy also increased the likelihood of introducing more amounts of stress and strains on the molds, before the actual testing.

Table 9.6: Details for strategies for demolding the concrete sample

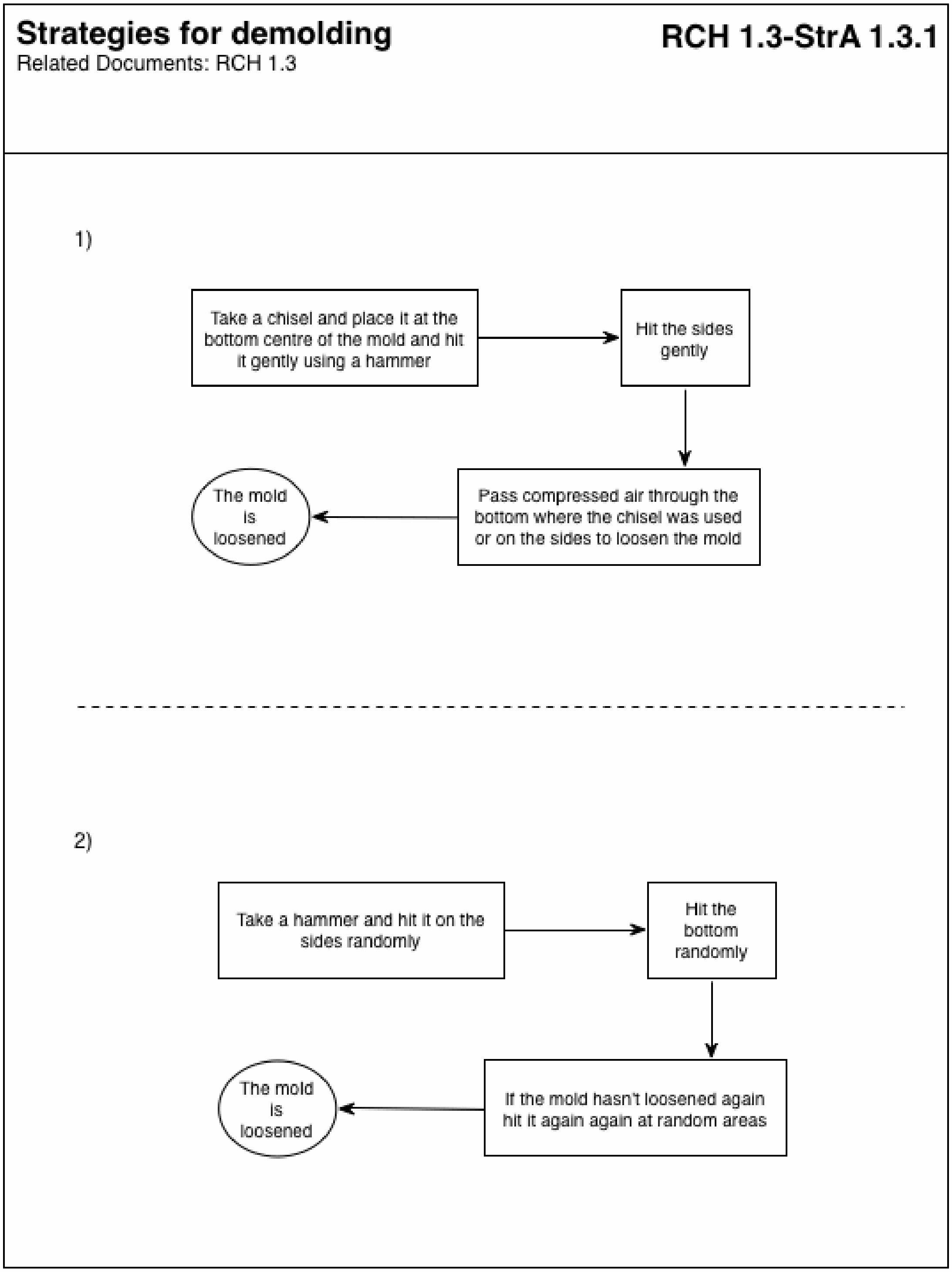


Figure 9.10: Strategies analysis for demolding for RCH Act for phase 1

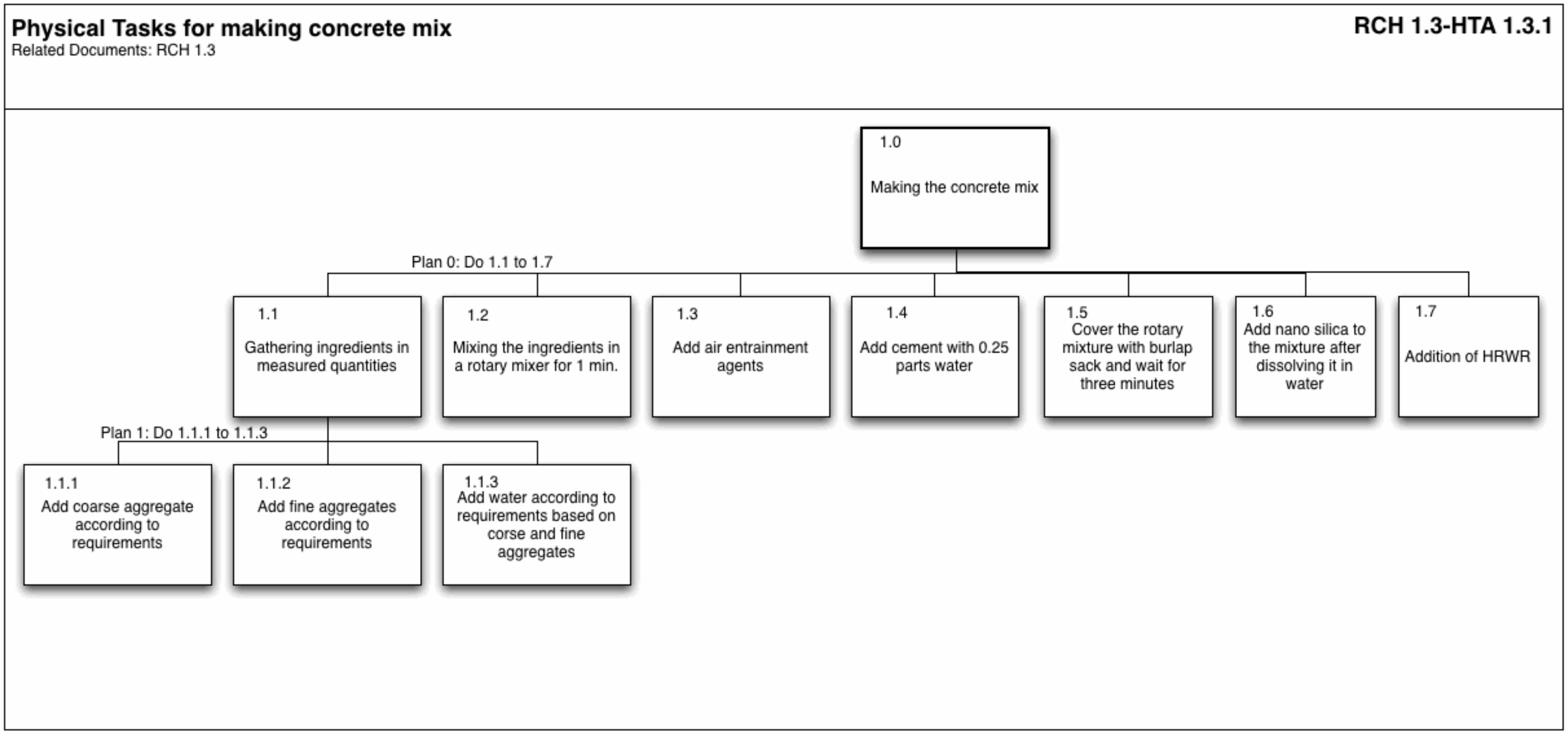


Figure 9.11: HTA for making concrete mix, related to RCH 1.3 for creation of concrete samples

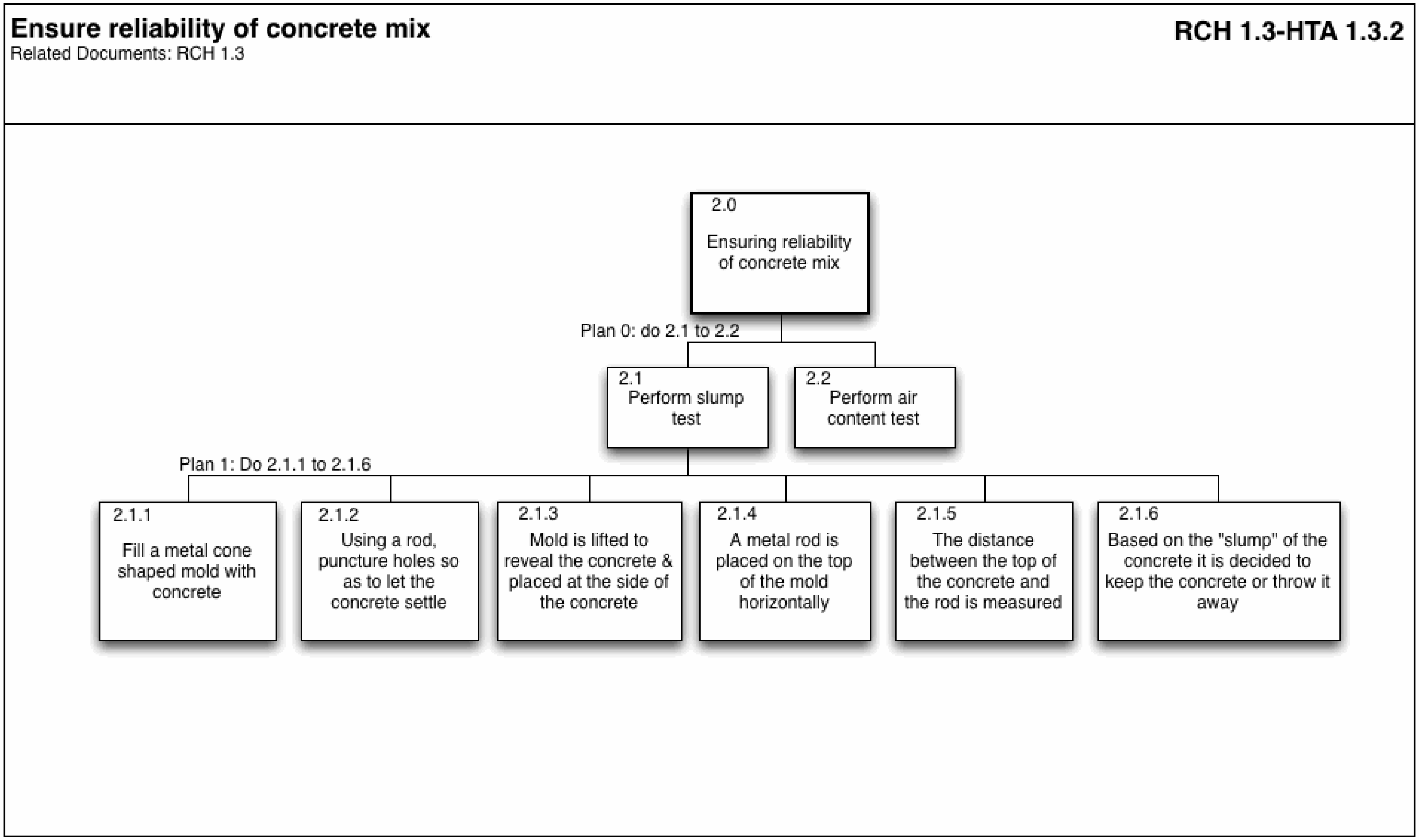


Figure 9.12: Physical tasks for ensuring reliability of the freshly created concrete for RCH 1.3 in phase 1

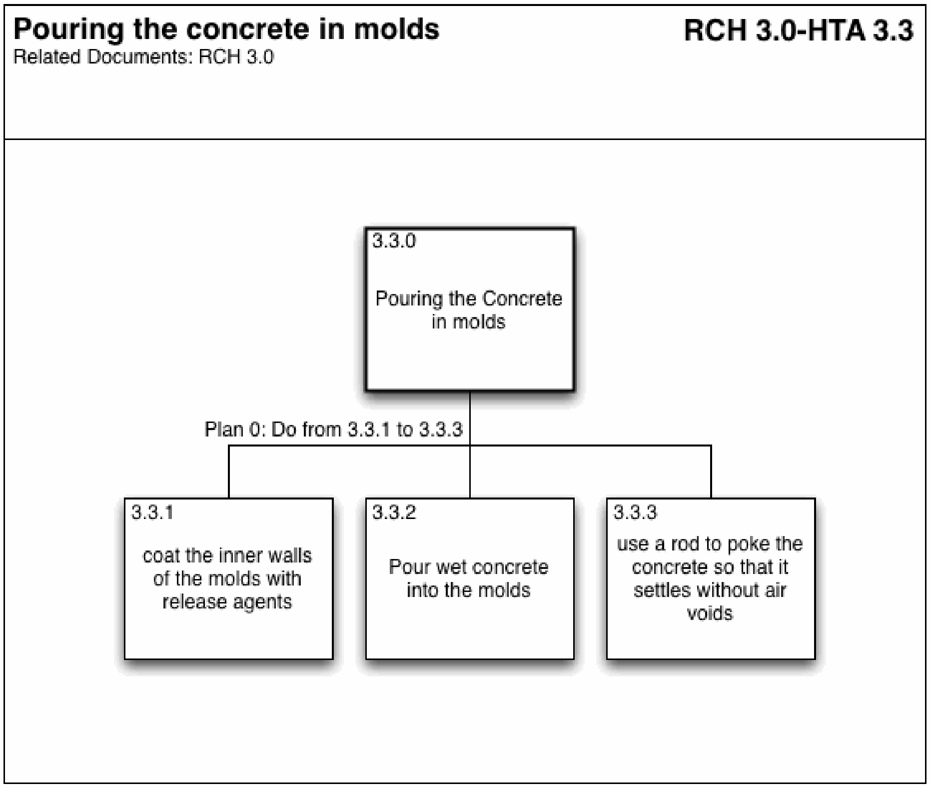


Figure 9.13: Physical tasks for pouring concrete in molds, related to RCH 1.3 in phase 1

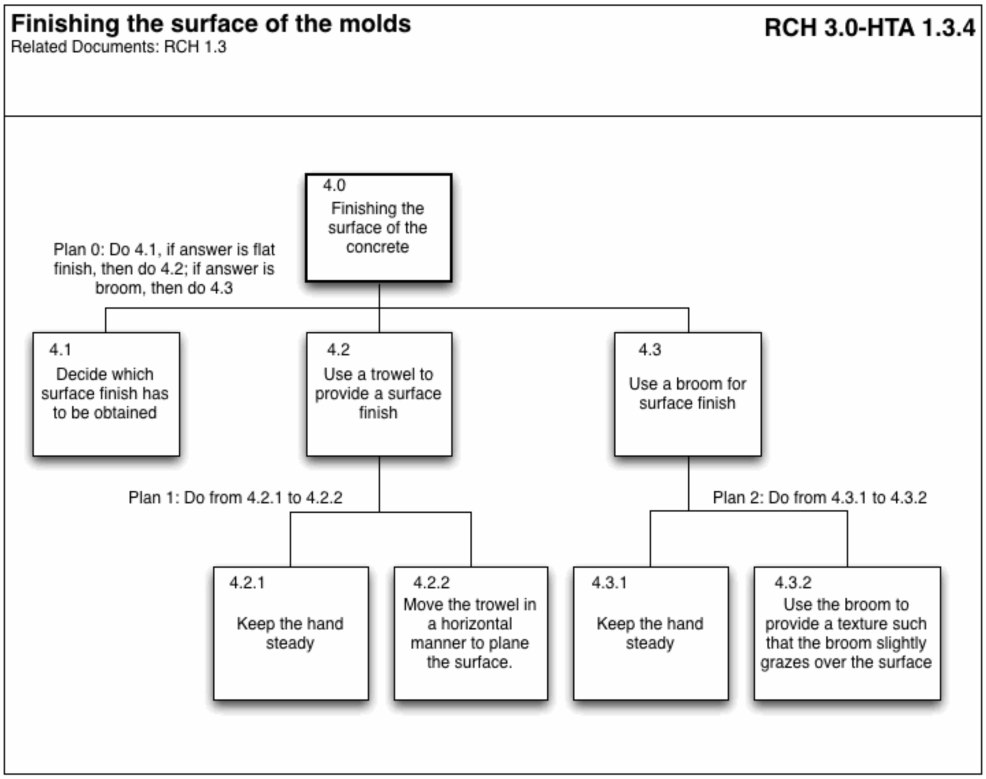


Figure 9.14: Physical tasks for finishing the surface of the concrete poured in the molds

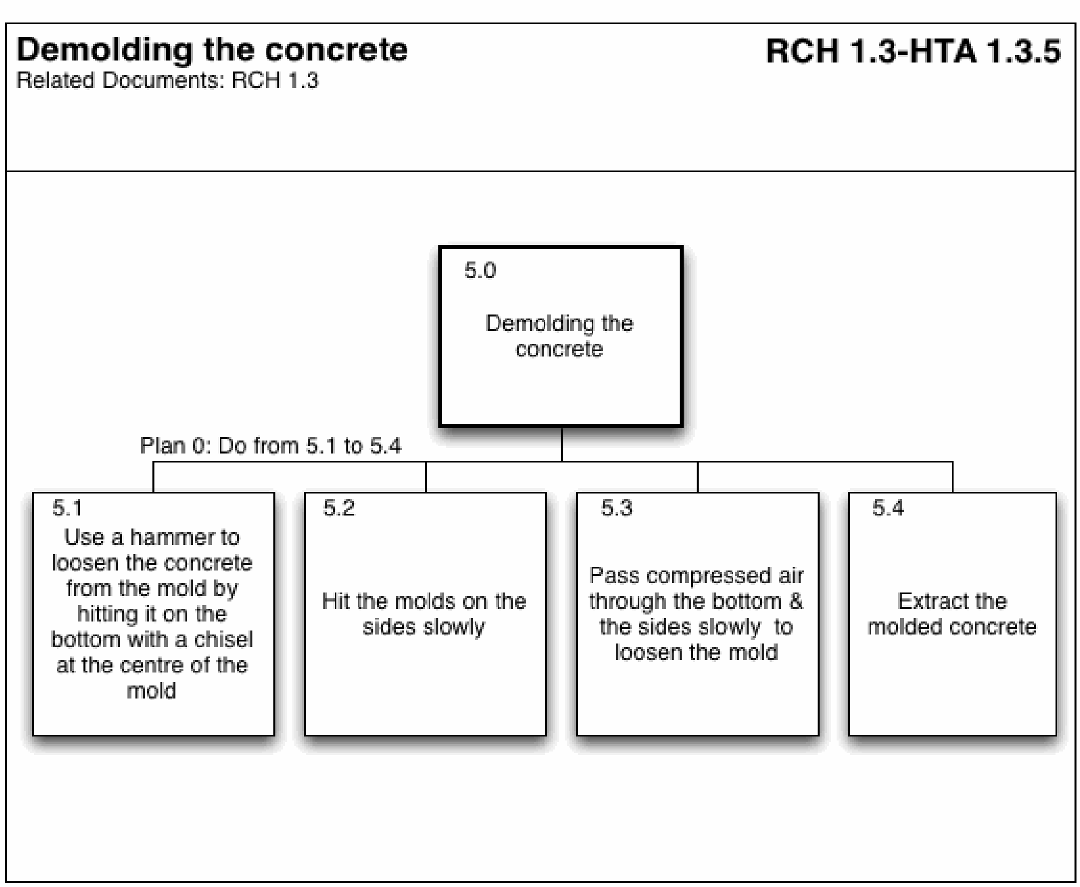


Figure 9.15: Physical tasks related to demolding the concrete, related to RCH 1.3 for phase 1

9.3.3 Comparison between CWA and WIDF for phase 1

Comparison between WIDF and CWA for Phase 1

	Comparison Criteria	**WIDF**	**CWA**
	RCH Environment (equivalent to AH in CWA)	Present	Present
47.	Functional Purpose	• Proper concrete samples based on project requirements	• Proper concrete samples based on project requirements
48.	Abstract Function	• Conservation of Mass for stoichimetric relations	• Conservation of Mass for stoichimetric relations

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
49.	Generalized Function	• Chemical processes related to creating fresh concrete • Physical and chemical processes related to creating samples from fresh concrete	• Chemical processes related to creating fresh concrete • Physical and chemical processes related to creating samples from fresh concrete
50.	Physical Function	• Coarse Aggregate • Fine Aggregate • Water (Hydrating Fluid) • Air Entraining Agent • HRWR • Portland Cement • Concrete Optimality Test Equipment • Demolding Equipment • Finishing Equipment • Nanosilica	• Coarse Aggregate • Fine Aggregate • Water (Hydrating Fluid) • Air Entraining Agent • HRWR • Portland Cement • Concrete Optimality Test Equipment • Demolding Equipment • Finishing Equipment • Nanosilica
51.	Physical Form	• Solid materials with diameter between 0.375 to 1.5 inches • Solid materials (particles) with diameter less than 0.375 inches • Liquid • Powder • Equipment according to ASTM standards • Hammer, Large Nail • Molds, Trowel • Nanoscale Particles	• Solid materials with diameter between 0.375 to 1.5 inches • Solid materials (particles) with diameter less than 0.375 inches • Liquid • Powder • Equipment according to ASTM standards • Hammer, Large Nail • Molds, Trowel • Nanoscale Particles
52.	Use value (affordances)	• Change in workability of materials • Hazardous for eyes,	

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
		respiration	
	RCH for Agent	Present	Not present as a whole except for SRK
53.	Intentions/ Personal Value Structures	• Make concrete samples ensuring proper procedures • Demold the concrete without damaging the samples	
54.	Abstract Information Processing / Psychological Laws/ Physical Laws	• Information processing and decisions made for creating the concrete samples	
55.	Psychological Mechanisms	• Decision making (based on materials & equipment) • Visual perceptual processes for mixing the concrete • Auditory processes involved in awareness of the changes of materials in the concrete mixing process • Visual and haptic perception processes for molding & surface finish • Visual & haptic perception processes for demolding.	
56.	Physiological Function	• Perceptual-motor coordination for mixing ingredients of the concrete • Perceptual-motor coordination for	

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
		making molds and surface finish • Perceptual motor coordination for demolding	
57.	Physical, Psychological Makeup/Anatomical form	• Proper mindfulness to apply concepts & assess situations while concrete mixing & molding & demolding process • Endurance for long hours of standing and physical labor for the concrete mixing & demolding process.	
	Capabilities (equivalent to SRK in CWA)		
58.	Skills	• Visual & haptic skills related to & mold-making process & demolding process; Dexterity for demolding • Visual & haptic skills related to concrete mixing process	• Visual & haptic skills related to & mold-making process & demolding process; Dexterity for demolding • Visual & haptic skills related to concrete mixing process
59.	Rules	• standardized rules related to the concrete mixing process • Heuristics related to mold-making & demolding process	• standardized rules related to the concrete mixing process creating the master mold • Heuristics related to mold-making & demolding process
60.	Knowledge	• Background knowledge of	• Background knowledge of

Comparison between WIDF and CWA for Phase 1			
	Comparison Criteria	**WIDF**	**CWA**
		concrete mixing process, abstract theory related to the chemical process related to concrete, among others • Knowledge of equipment and usage	concrete mixing process, abstract theory related to the chemical process related to concrete, among others • Knowledge of equipment and usage
	RCH -Act	Present	Not present as a whole (except for Decision Ladder and Strategies Analysis)
61.	Functional Purpose	• Proper concrete samples based on project requirements	
62.	Abstract information processing/ Meaning Processing Activities (equivalent to Decision Ladder in CWA)	• Information processing related to making concrete samples	• Information processing related to making concrete samples
63.	Generalized Strategies (equivalent strategies analysis in CWA)	• Strategies for demolding	• Strategies for demolding
64.	Physical Tasks	• Making the concrete sample • Ensuring reliability of concrete mix • Pouring concrete in the molds • Finishing surface of the concrete in molds • Demolding the concrete samples	
65.	Bodily/Physical changes (automatic)	• Automatic adjustments during physical tasks. Changes in posture & other adjustments related to task	

Comparison between WIDF and CWA for Phase 1

	Comparison Criteria	**WIDF**	**CWA**
		demands	
66.	Interpreted Value	• Could be interpreted as conscious shifts; thus, provide ambiguity in partitioning the task flow for an external observer	

Table 9.7: Comparison between CWA and WIDF for phase 1

9.4 Phase 2—Testing nanoconcrete samples

In phase 1, the main aim was to create nanoconcrete and use it to make samples for testing. In the next phase 2, the testing of concrete is discussed in detail. In modeling the phase, the system formulation is considered at a broader level of tests rather than at the level of individual tests. This broad granularity of models is intentionally chosen as broad because the individual tests are not stringent but depend on the research project. Therefore, depending on the specifics of individual research projects, researchers select tests that would be done on the samples. As described in chapter 9a, for the project related to nanoconcrete, a few tests were conducted by the researcher. These include, compression test, sound absorption tests, British pendulum test, sand patch test and abrasion test. The present phase 2 is developed taking this high level view on the system formulation.

A further notable aspect of the modelling of this phase is the manner in which the system is modelled. Selection of tests and the test itself, are aspects that cannot be strictly reduced to physical choices. Therefore, the scientific values and priorities related to testing are to be included in the models. Further, due to the granularity selected for modelling the present phase, there is a need for incorporating the various tests under one overarching scheme. Consideration of scientific values and priorities involved in the testing provides this unifying rubric for understanding the different tests and their related activities in terms of the entire system functioning. To model this phase, the rest of the chapter follows the same structure as that presented in phase 1. First, the models related to CWA are presented, followed by those of WIDF. Finally, the design requirements gleaned from both of these are compared to each other.

9.4.1 CWA

9.4.1.1 WDA

The first step of the CWA is the WDA and the abstraction hierarchy for this phase 2 is presented as AH 2.0 (Figure 9.16). At the topmost level, the functional purpose of the system is to gather data from the nanoconcrete samples using various tests. The next level of abstract function, includes the balance of scientific values and priorities related to testing of the samples, as well as information flow through the system. In terms of information flow, the nanoconcrete sample acts as the source of the information. After being subjected to tests, the information is transformed by the use of equipment and can be gleaned from the system and stored in secondary form such as in paper or electronic media. Also, as mentioned in the system formulation, phase 2 related to testing involves certain scientific values and priorities that are not physical in nature but can be understood as “soft constraints”. For example, in the present work domain, the physical tests are chosen and conducted based on scientific values and priorities (soft constraints on physical values). Both the scientific values and priorities mutually constrain each other and remain constant throughout the functioning of the system. Thus, they are modeled in terms of balanced qualities (for a similar strategy for modelling, see Burns & Hajdukeiwicz, 2004, Ch. 5).

In the third level of generalized function, the processes related to testing the concrete samples are addressed. These processes will be described in detail in the causal representation of AH (AH 2.1, Figure 9.17). At the next level of physical function, there are the equipment and their capabilities that instantiate the various processes at the upper level of generalized function. These equipment include compression testing equipment, British Pendulum test equipment, among others. Finally, at the level of physical form, the details of the equipment are provided. For example, in case of the British Pendulum test, the standard equipment and standardized rubber according to ASTM standards are to be used.

The abstraction hierarchy can have a separate representation in terms of a causal structure. This causal representation is developed in AH 1.1. In this causal representation two representations are developed in detail. First, the level of abstract function has two interacting entities related to the balance of scientific values and priorities related to the testing. Both these entities are present at all times and mutually constrain each other for the functioning of the domain. These mutual interacting entities have an effect on the information flow that exists at the various levels of abstraction. The flow of information begins from the source (concrete sample) and finally gets stored into electronic/physical media.

At the next level of generalized function, two main flows are noticed, both beginning from the concrete sample and ending with the discarding of the sample. As it is to be recalled from chapter 8a, two sets of samples are to be used. The first set involves shorter samples while the second set involves taller samples. The shorter samples are first used for the sound absorption test. Next, they are used for the British Pendulum test and sand patch test. Finally, after being used for the abrasion test they are discarded. This is because up till the sand patch test, there are no material-based changes in the concrete sample. However, after the abrasion test, the material loses weight due to the wearing away of the top surface and are discarded. In contrast to the sequence of processes involving the smaller samples, the taller samples are used only for the compression tests. Compression tests measure the ability of the samples to withstand pressure; therefore, during the tests, the samples crack. After the test these samples are discarded.

Along with the causal representation, phase 2 can also be addressed in terms of abstraction-decomposition space (WDA 2.0, Figure 9.18). In this domain, the decomposition is handled in terms of two main levels of system and sub-system. The sub-system level is divided in terms of the five test subsystems. At the overall systemic level the function is to gather data from the samples by various tests. At the abstract function level of subsystems, there is a balance to be maintained for scientific values and priorities related to the testing of samples. Along with the soft constraints, there is flow of information from the source to the storage. At the generalized function level, each test subsystem has their individualized processes and depends on the aspect that they are being used for in the research project. At the level of physical function, the various equipment used for the individual tests are considered. Depending on the tests, these equipment have their unique characteristics. Finally, at the level of the physical form for the subsystem, the physical aspects of the equipment required for the various tests are considered.

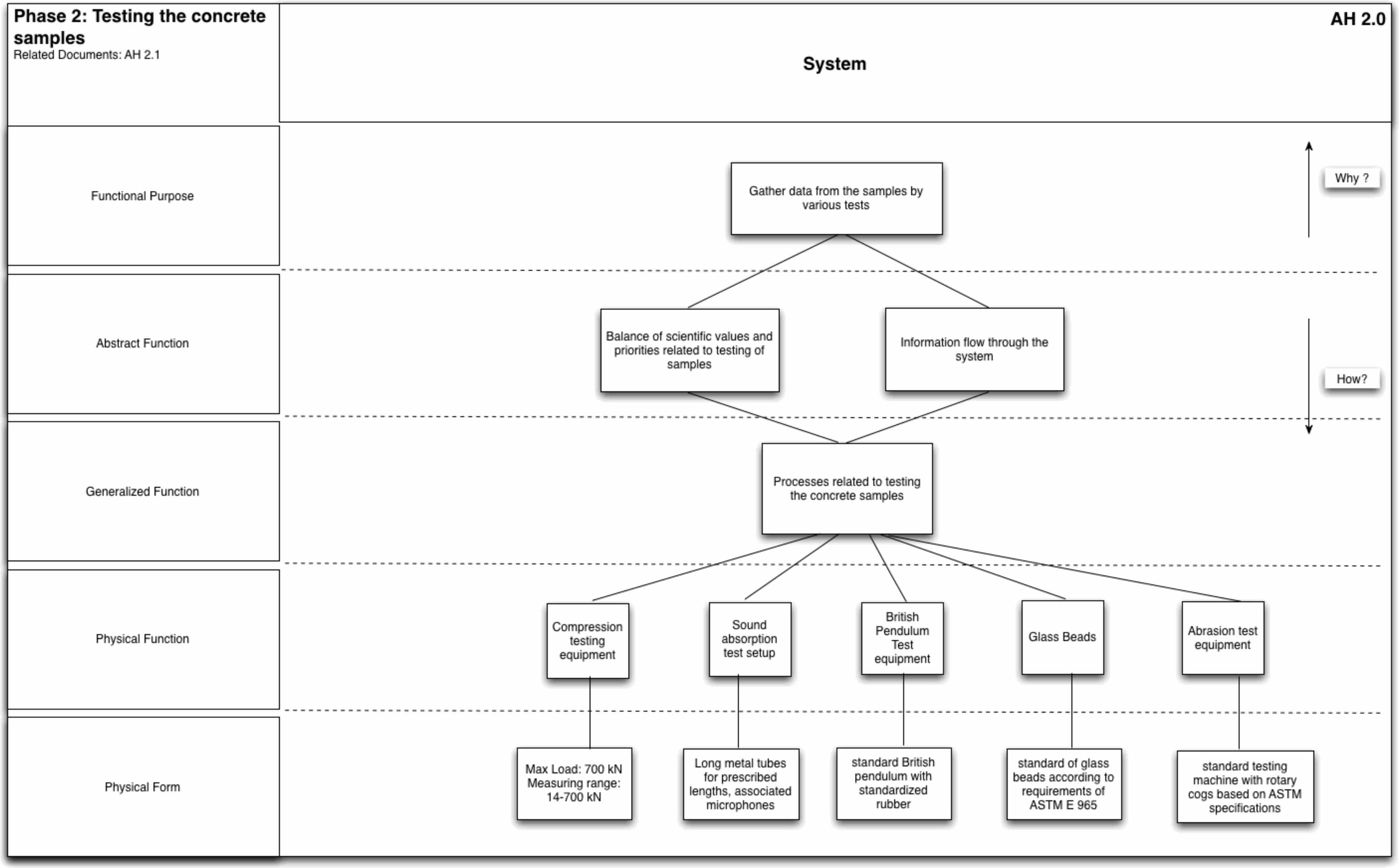


Figure 9.16: AH for phase 2, testing the samples

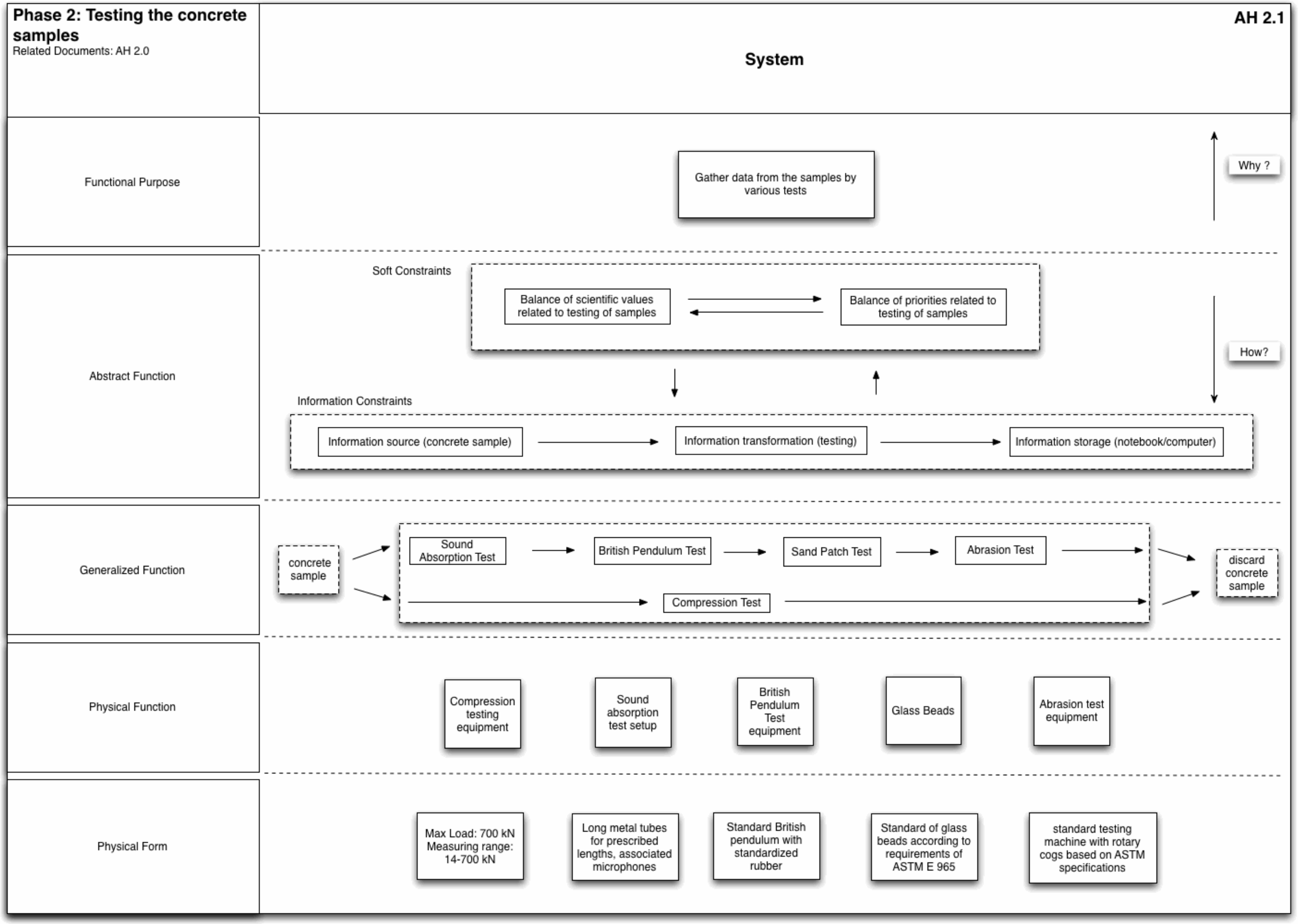


Figure 9.17: Causal representation of AH for phase 1, testing the sample

Phase 2: Testing the concrete samples
Related Documents: AH 2.0, AH 2.1

WDA 2.0

	System	**Sub-System**				
		Compression test subsystem	Sound Absorption test subsystem	British Pendulum test subsystem	Sand Patch test subsystem	Abrasion test subsystem
Functional Purpose	Gather data from the samples by various tests					
Abstract Function		← Balance of scientific values and priorities related to testing of samples → ← Information Flow from the source to storage →				
Generalized Function		Compression testing process	Sound absorption test process	British Pendulum Test process	Sand Patch Test Process	Abrasion test Process
Physical Function		Compression testing equipment	Sound absorption test setup	British Pendulum Test equipment	Glass Beads	Abrasion test equipment
Physical Form		Max Load: 700 kN Measuring range: 14-700 kN	Long metal tubes for prescribed lengths, associated microphones	Standard British pendulum with standardized rubber	Standard of glass beads according to requirements of ASTM E 965	Standard testing machine with rotary cogs based on ASTM specifications

Figure 9.18: Abstraction decomposition space for phase 2 testing the concrete

9.4.1.2 ConTA

After the work domain analysis, the second step of CWA consists of the ConTA. In the present work domain, the control task analysis has been addressed at a very high level of overall tests rather than considering the control tasks involved at the level of each test. This level of modelling for ConTA is in accordance with the system formulation. The figure below illustrates (Figure 9.19) the steps involved in ConTA.

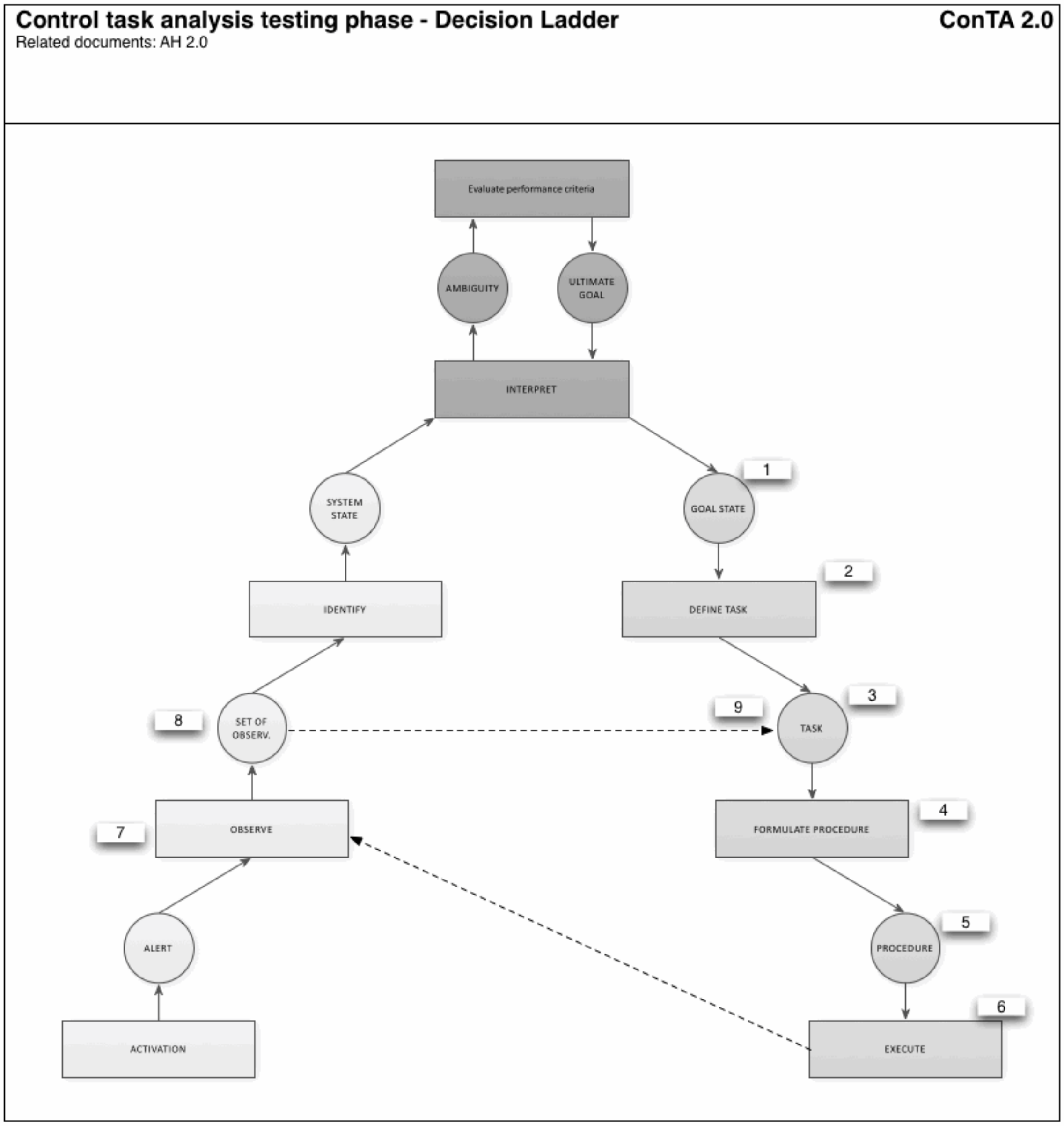


Figure 9.19: Control Task analysis for testing samples

Control task analysis of testing samples-Decision Ladder Related documents: AH 2.0				**ConTA 2.0**
Number	**Ladder Code**	**Notes**	**Type**	**Abstraction Level**
1	Goal state	Identification of the type and number of tests to be conducted on the concrete	Knowledge State	Functional Purpose, Abstract Function
2	Define Task	Definition of the associated tasks required for the tests	Information Processing Activity	Generalized function, Physical function
3	Task	A task state is formulated based on the various tasks involved in the tests	Knowledge State	Generalized function, Physical function
4	Formulate procedures	A detailed set of procedures are formulated on the number of tests and tasks, as well as the order in which they are executed	Information Processing Activity	Physical Function
5	Procedure	Sets of procedures are formulated into a state based on the order in which the tests are to be conducted. For e.g. the compression tests require different samples (tall samples); whereas, the other tasks are conducted on the same set of samples (short samples)	Knowledge State	Physical Function, Physical Form

6	Execute	The planned tests are executed, beginning with the first set involving compression test	Activity	Physical Form
7	Observations	Information about the outcome is observed and recorded in form of experimental data	Information Processing Activity	Generalized Function, Physical Function, Physical Form
8	Set of observations	Based on the observed information, an observation set is formed regarding the results of the administered tests	Knowledge State	Generalized Function
9	Task	Reformulate the task state in light of completed tests and goal state	Knowledge State	Generalized Function, Physical Function

Table 9.8: Details of control task analysis for concrete testing

9.4.1.3 StrA

After the ConTA, in the third phase of StrA, strategies for conducting tasks are considered. As it was mentioned earlier in chapter 9a, the strategies for particular tests are often circumscribed due to the nature of the guidelines set forth by ASTM. However, in some cases, the researchers still use strategies in their work. For example, in case of the British Pendulum test, the researchers reduce the turn around time for testing, by the following strategies (Str 2.1, Figure 9.20).

Strategies analysis for minimizing turn around time for testing Related documents: AH 2.0, DL 2.0	**StrA 2.1**
1	The first strategy for decreasing turn around time lies at the level of the particular test. For example, in the case of British Pendulum test, two people are involved in conducting the test. The division of labor in this particular test is in terms of one person wetting the sample, measuring the temperature of the wet surface and noting the readings. The second person conducts the test and verbalizes the results. The first person noted down the results, verbalized by the second person. This strategy reduces the turn around time of the test.
2	The second strategy for minimizing the turn around time consists of doing the steps in a manner so that the time required for it is reduced internally. For example, in the British Pendulum test, the concrete sample is made wet for conducting the tests. After this test, the molds need to be dry for the next sand patch test. Therefore, instead of letting the sample dry on their own, they are placed under a fan as soon as the test gets over. This allows for drying the sample faster. If the molds are not dry before the sand patch test, then they are given some more time to dry further. Thus, steps such as the above minimize the turn around time for conducting the test.

Table 9.9: Details of strategies used in British Pendulum test

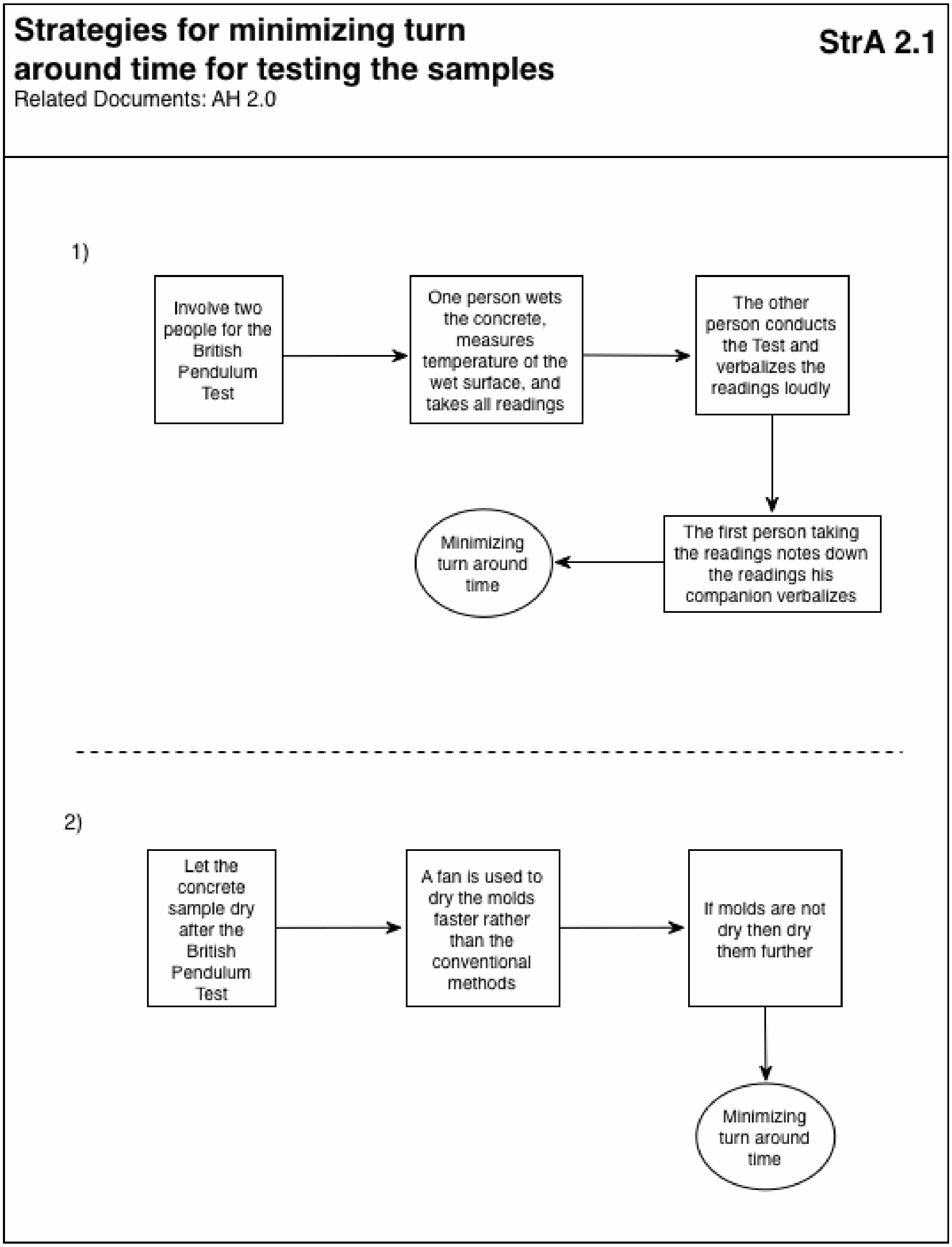


Figure 9.20: Strategies for minimizing turn around time for testing the sample

9.4.1.4 WCA

The final step of the CWA is the WCA. In this step, the competencies in terms of skills, rules and knowledge are addressed. The following figure discusses the details of the SRK taxonomy as applied to the present work domain (SRK 2.0, Table 9.10).

Worker competencies analysis for testing concrete samples Related documents: AH 2.0				**WCA 2.0**
Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge-Based Behavior**
Associated Number	**Associated Number**			
	Goal state			Background disciplinary knowledge of concrete and the research agenda are required, for formulating the type and numbers of tests to be conducted on concrete
	1			
Define Task	Task		Formalized rules associated with the different tests prescribed by the governing bodies	Reasoning required for selection of proper tests based on the research questions
2	3,9			

Formulate procedures	Procedures	Perceptual-haptic knowledge required for each test, for e.g. in the sand patch test, there is the need for spreading the sand evenly on the concrete surface	Heuristics for conducting the tests one after the other in a phased manner to optimally utilize research time	Knowledge about background of standards and the process of conducting these tests as per the required governing bodies.
4	5			
Execute		Perceptual-haptic knowledge required for orchestrating the suite of tests	Heuristics for conducting the tests in a seamless manner based on available time and manpower. For e.g. in case of the British Pendulum test, if two people are involved, then one wets the surface while the other takes the readings and verbalizes it. This coordination and rules for division of labor is necessary for conducting the tests	
6				
Observations	Set of Observations	Perceptual skills required for noting the results of the tests		Background knowledge about the research program to comprehend the results.
7	8			

Table 9.10: Skills, Rules and Knowledge required for testing the concrete samples

9.4.2 WIDF

9.4.2.1 RCH Environment

In case of WIDF, phase 2 can be addressed beginning with the RC hierarchy for environment (RCH 2.1, Figure 9.21). In the first level of RCH environment, the functional purpose consists of gathering data from the samples by various tests. At the next level of abstract function, there are two entities related to information flow through the system and balance of scientific values and priorities related to the testing. The information flow through the system takes into account the gleaning of data from the samples and ultimately recording it. In contrast, the scientific values and priorities are soft constraints that enable the entire system of testing to function properly. Both these entities will be developed further in the causal representation of the RCH environment (RCH 2.1.1)

In the third level of generalized function, the processes related to the testing of the concrete samples are present. These processes require certain equipment and associated characteristics that are developed in the level pertaining to the physical function. For example, this level includes equipment related to British Pendulum test. The equipment for the British Pendulum test has a certain description in terms of its capabilities. Further, the British Pendulum test requires a specialized pendulum setup along with standardized rubber based on ASTM standards. Also, to conduct the sand patch test, standard glass beads are required based on the criteria of ASTM. These aspects of physical make-up of the equipment and associated paraphernalia are located in the level pertaining to physical form.

Finally, at the level of use values or affordances, if the equipment is not used properly, it may cause problems. To substantiate, there are formal criteria and procedures to use any given equipment (generally based on ASTM criteria), as well as physical harm is possible if used in a manner different from the specified procedures, the data collection will not be proper. For example, the British pendulum test requires a standard procedure consisting of the wetting the sample and noting the temperature for simulating wet-road conditions. The pendulum is then released from a particular height. If the use of the equipment is not done properly in the designated manner, faulty data will be collected. Therefore, even though the pendulum affords being dropped from different positions, to successfully record proper data, it should be dropped from the designated height.

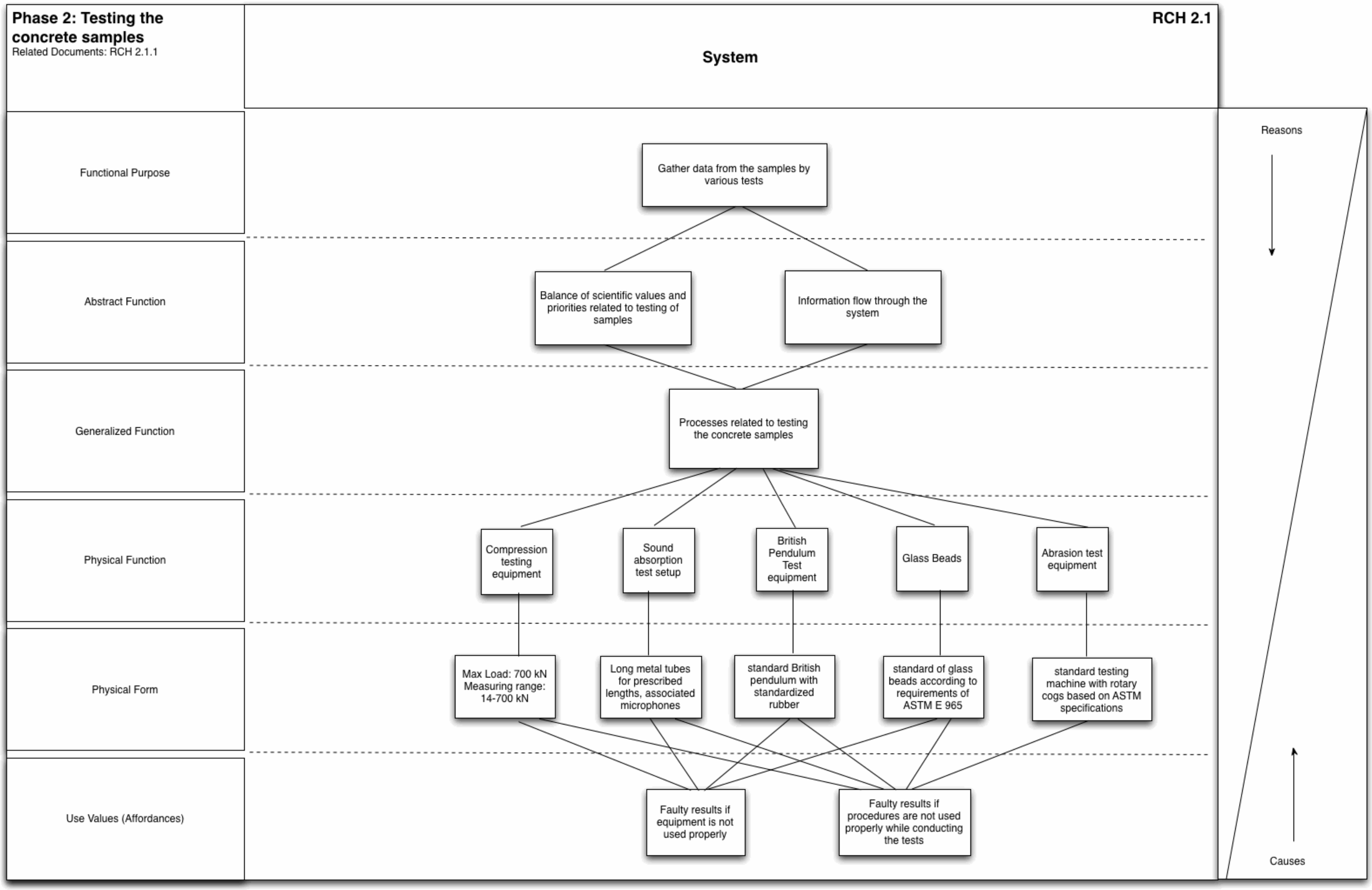


Figure 9.21: RCH environment for phase 2 of testing the molds

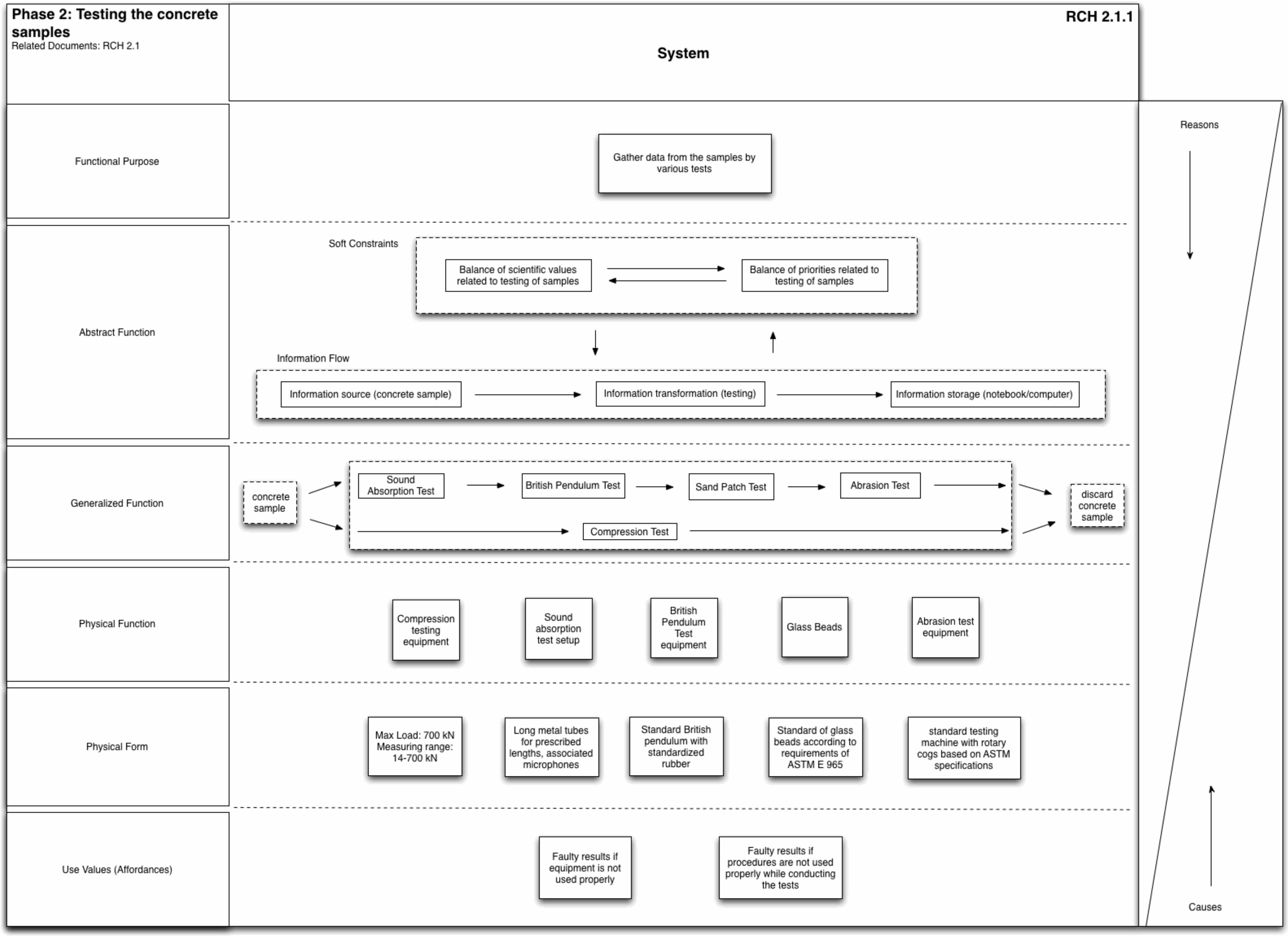


Figure 9.22: Causal representation of the RCH environment for testing concrete samples

Phase 2: Testing the concrete samples
Related Documents: RCH 2.1, RCH 2.1.1

RCAH 2.1

	System	**Sub-System**				
		Compression test subsystem	Sound Absorption test subsystem	British Pendulum test subsystem	Sand Patch test subsystem	Abrasion test subsystem
Functional Purpose	Gather data from the samples by various tests					
Abstract Function		← Balance of scientific values and priorities related to testing of samples → ← Information Flow from the source to storage →				
Generalized Function		Compression testing process	Sound absorption test process	British Pendulum Test process	Sand Patch Test Process	Abrasion test Process
Physical Function		Compression testing equipment	Sound absorption test setup	British Pendulum Test equipment	Glass Beads	Abrasion test equipment
Physical Form		Max Load: 700 kN Measuring range: 14-700 kN	Long metal tubes for prescribed lengths, associated microphones	Standard British pendulum with standardized rubber	Standard of glass beads according to requirements of ASTM E 965	Standard testing machine with rotary cogs based on ASTM specifications
Use Values (Affordances)		← Faulty results if equipment is not used properly → ← Faulty results if procedures are not followed properly while conducting the tests →				

Figure 9.23: Abstraction decomposition space for RCH Environment for testing the samples

The RCH environment can also be addressed in terms of a causal representation (RCH 2.1.1, Figure 9.22). In this causal representation, the levels of abstract function and generalized function are developed in greater detail. At the level of abstract function, a demarcation is made between two categories of soft constraints and information flow. The soft constraints include a balance of scientific values related to the testing and balance of priorities related to the testing of samples. To substantiate, the scientific values required for testing involves strict adherence to specified procedures for data collection. Further, there is a balance of priority of tests and the use of particular samples based on those priorities for successful data collection. Both the notion of scientific values and priorities mutually constrain each other. These two soft constraints are also interacting with the information flow. The information flow begins at the source; i.e., the concrete sample from which the information has to be derived. Next due to the testing, information transformation takes place. In this transformation, the equipment transforms the information in its material forms to numerical form. These numerical values are then stored in paper or electronic media.

After the description of the entities at the level of abstract functions, the level of generalized function consists of two parallel sets of processes. The first process involves testing shorter samples. The shorter samples are first tested for their sound absorption capabilities. Then, frictional properties are tested by the British Pendulum test. Next, the sand patch test and abrasion test are conducted on the samples. After the abrasion test, the samples are discarded. The second process at the level of generalized function, involves the taller concrete samples. Here these samples undergo compression tests. In this compression testing process, the samples crack due to the excessive pressure and are later discarded after the test. Both these categories together comprise the level of generalized function.

Along with the causal representation, the abstraction-decomposition space can be charted for phase 2 for testing (Figure 9.23). In this case, the system is broken into the subsystems comprising of compression test, sound absorption test, British Pendulum test, sand patch test and abrasion test sub systems. For each of these subsystems, the balance of scientific values and priorities and information flows occur from the source to the storage. Therefore, at the level of abstract function, the scientific values, priorities and information flows put together are required for all subsystems. At the level of generalized function, each of the tests, have their own processes. For example, the compression test requires a process different from British Pendulum test. Therefore, the processes are divided according to subsystems. Similarly, at the level of physical function and physical form the entities are divided based on different subsystems. Finally, at the level of use-values and affordances, the faulty results may be obtained if either the equipment is not used properly or procedures are not followed properly while conducting the tests. These aspects are prevalent for all the tests and thus are represented as being common for all subsystems.

9.4.2.2 RCH Agent

After the RCH environment, the next RC hierarchy to be considered is that of the agent (RCH 2.2, Figure 9.24). In this hierarchy, the first level considers the intentions to test the concrete samples according to the tests required for the particular projects. The next level of abstract information processing/ psychological laws/physiological laws accounts for the information processing for operating equipment and testing samples. Next at the level of psychological/physiological mechanisms, visual attention is required for testing the molds. At the fourth level of psychological/physiological function, there is perceptual-motor coordination for operating equipment and instruments during testing process. Further, at the fifth level of physical, psychological makeup/anatomical form, there is the need for proper mindfulness to assess problems leading to data recording and testing as well as the endurance for long hours of testing. Finally, at the level of capabilities, the dimensions of skills and knowledge are explored. In terms of skills, dexterity is required for operating the test equipment for conducting the tests. In terms of rules, the various standardized rules related for using equipment correctly are to be accounted. To enable the overall system to function correctly, there is the need to account for background knowledge related to concrete mixing process, abstract theory related to the properties of concrete with them. Further, there is also the necessity for having knowledge of the equipment required for concrete testing. The skills rules and knowledge entities are discussed in details in SRK 2.0 (Table 9.11).

Worker competencies analysis for testing concrete samples **SRK 2.0**
Related documents: RCH 2.0

Information Processing /Activity Step (Ladder Code)	**Resultant state (Ladder Code)**	**Skill-Based Behavior**	**Rule- Based Behavior**	**Knowledge-Based Behavior**
Associated Number	**Associated Number**			
	Goal state			Background disciplinary knowledge of concrete and the research agenda are required, for formulating the type and numbers of tests to be conducted on concrete
	1			
Define Task	Task		Formalized rules associated with the different tests prescribed by the governing bodies	Reasoning required for selection of proper tests based on the research questions
2	3,9			

Formulate procedures	Procedures	Perceptual-haptic knowledge required for each test, for e.g. in the sand patch test, there is the need for spreading the sand evenly on the concrete surface	Heuristics for conducting the tests one after the other in a phased manner to optimally utilize research time	Knowledge about background of standards and the process of conducting these tests as per the required governing bodies.
4	5			
Execute		Perceptual-haptic knowledge required for orchestrating the suite of tests	Heuristics for conducting the tests in a seamless manner based on available time and manpower. For e.g. in case of the British Pendulum test, if two people are involved, then one wets the surface while the other takes the readings and verbalizes it. This coordination and rules for division of labor is necessary for conducting the tests	
6				
Observations	Set of Observations	Perceptual skills required for noting the results of the tests		Background knowledge about the research program to comprehend the results.
7	8			

Table 9.11: Skills, rules and knowledge for RCH Agent

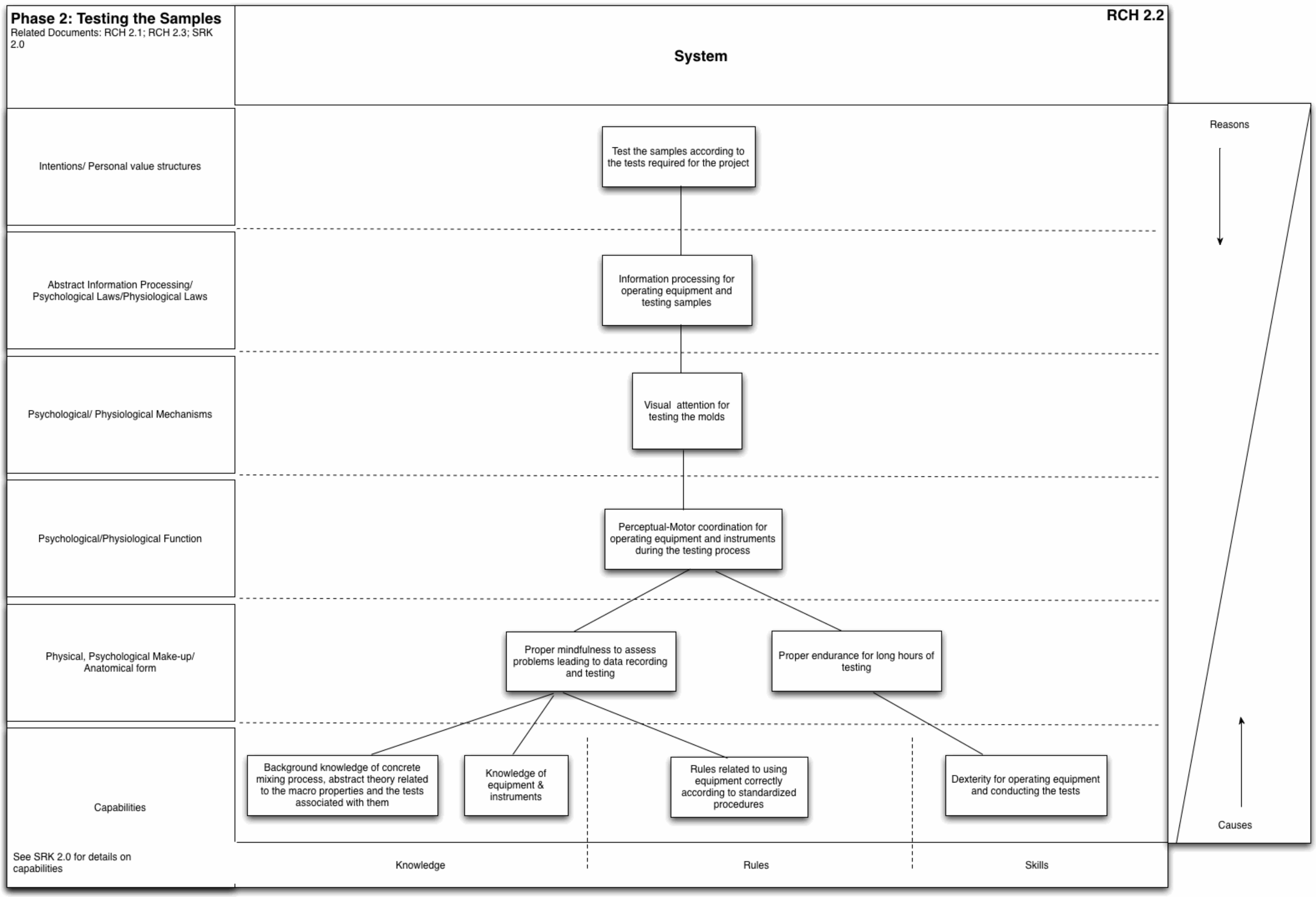


Figure 9.24: RCH agent for phase 2 of testing the molds

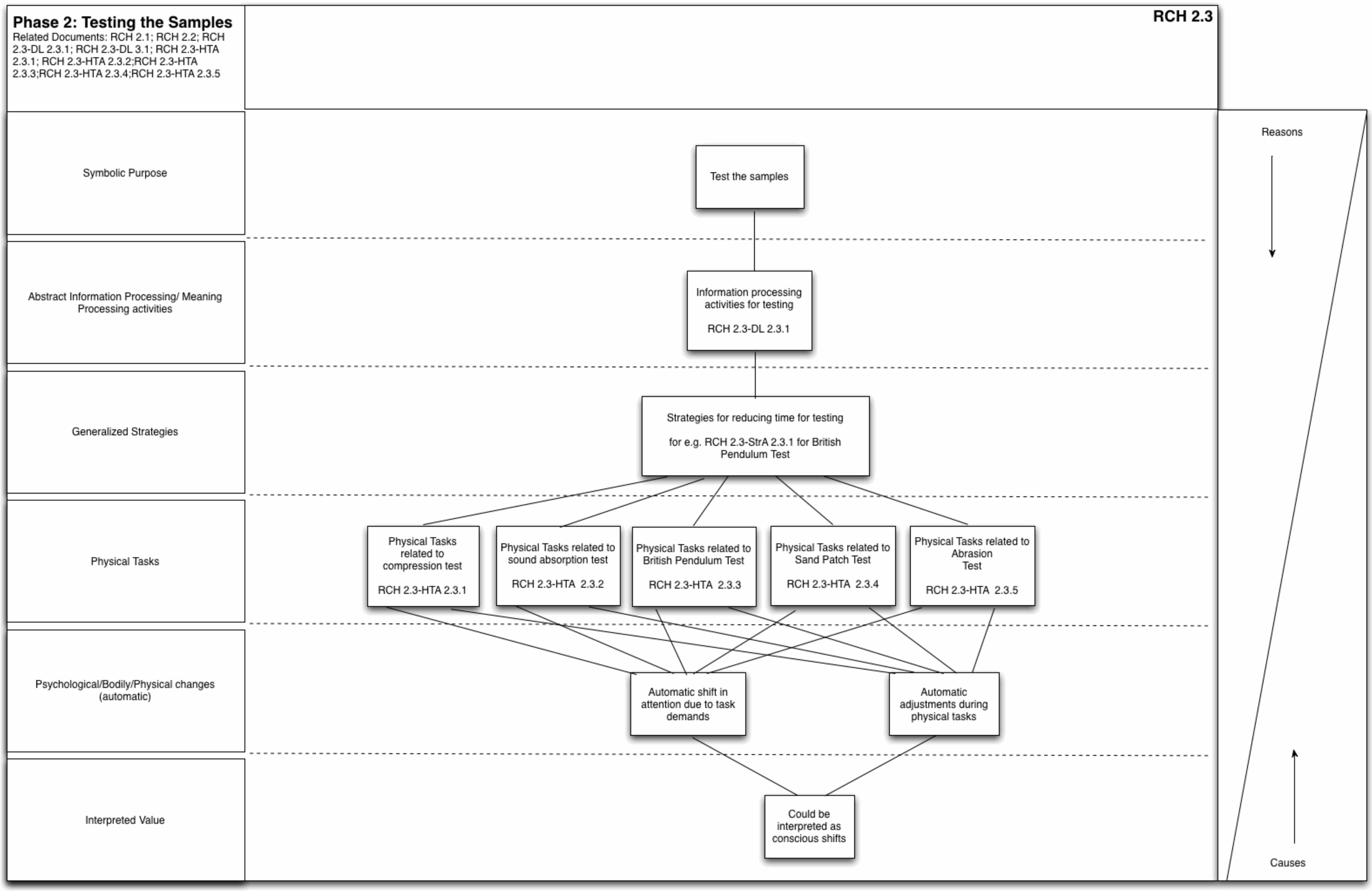


Figure 9.25: RCH Act for phase 2 of testing the molds

9.4.2.3 RCH Act

The third RC hierarchy consists of acts (RCH 2.3, Figure 9.25). At the very first level, there is the symbolic purpose of testing the samples. At the next level related to information processing/meaning processing activities, there is information processing related to testing. The information processing activities have ben developed in detail using the decision ladder (RCH 2.3-DL 2.3.1, Figure 9.26).

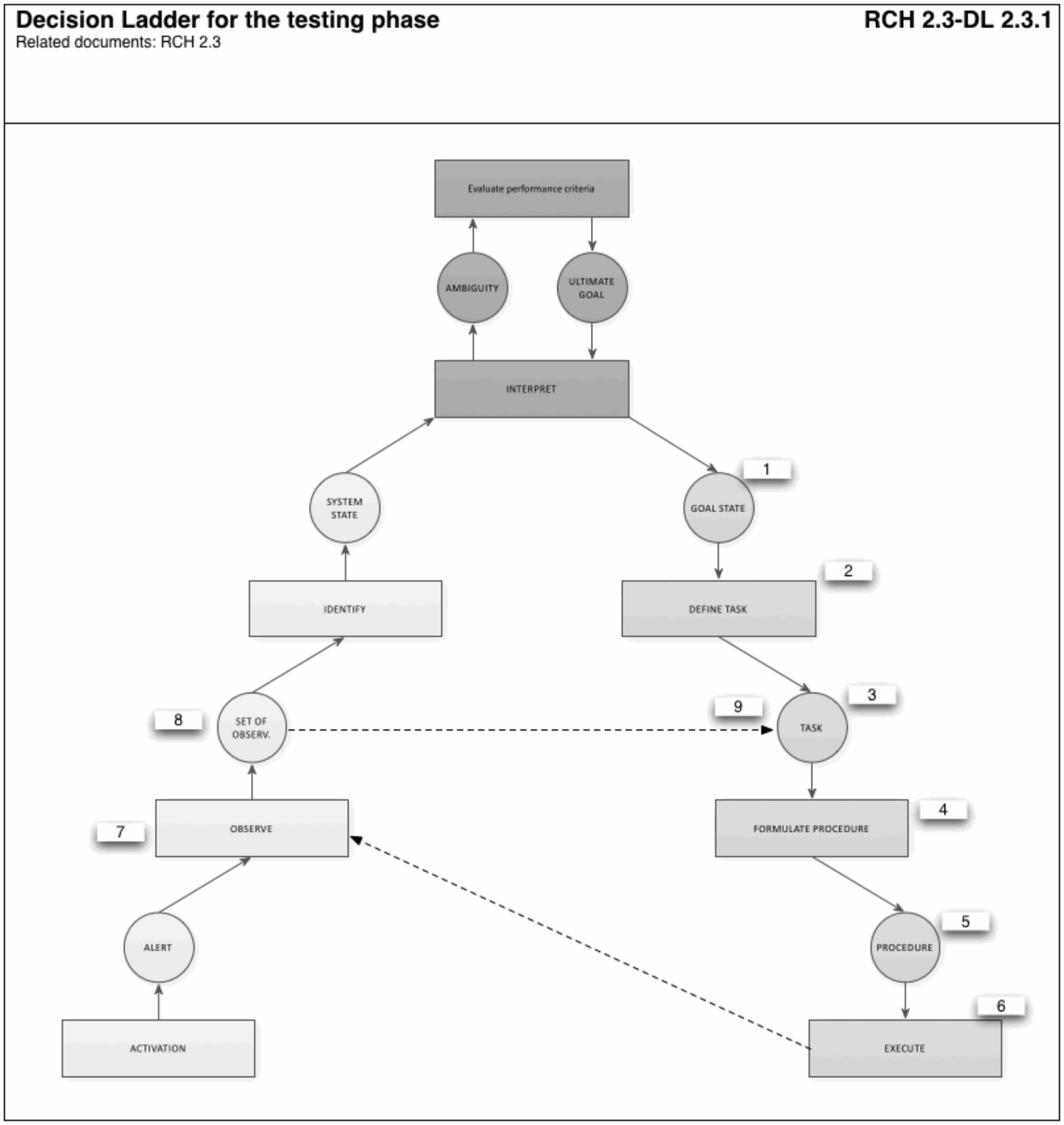


Figure 9.26: Information processing activities for testing phase

After the information processing activities, the generalized strategies are listed. It is to be noted that the testing procedure is standardized by agencies such as ASTM. As a result, researchers have less leeway to develop their own strategies. Despite this challenge, during this second phase related to testing, one major strategy (for a particular test) emerged as salient during the testing process. Namely, researchers tried to reduce time required for testing for the British Pendulum test. This strategy is discussed in detail and highlights how the researchers cut down time by either conducting the tests with more manpower or by selecting alternatives to speed up sections of the testing process. These two strategies are listed below (RCH 2.3–Str 2.3.1, Figure 9.27).

Strategies for minimizing turn around time for testing Related documents: RCH 2.3	**RCH 2.3- StrA 2.3.1**
1	The first strategy for decreasing turn around time lies at the level of the particular test. For example, in the case of British Pendulum test, two people are involved in conducting the test. The division of labor in this particular test is in terms of one person wetting the sample, measuring the temperature of the wet surface and noting the readings. The second person conducts the test and verbalizes the results. The first person noted down the results, verbalized by the second person. This strategy reduces the turn around time of the test.
2	The second strategy for minimizing the turn around time consists of doing the steps in a manner so that the time required for it is reduced internally. For example, in the British Pendulum test, the concrete sample is made wet for conducting the tests. After this test, the molds need to be dry for the next sand patch test. Therefore, instead of letting the sample dry on their own, they are placed under a fan as soon as the test gets over. This allows for drying the sample faster. If the molds are not dry before the sand patch test, then they are given some more time to dry further. Thus, steps such as the above minimize the turn around time for conducting the test.

Table 9.12: Details of the strategies for minimizing turn around time for testing

At the next level related to physical tasks, the tasks are described in detail. These include physical tasks for compression test (RCH 2.3-HTA 2.3.1, Figure 9.28); physical tasks related to the sound absorption test (RCH 2.3-HTA 2.3.2, Figure 9.29); physical tasks related to the British pendulum test (RCH 2.3-HTA 2.3.3, Figure 9.30); physical tasks related to sand patch test (RCH 2.3-HTA 2.3.4, Figure 9.32); physical tasks related to abrasion test (RCH 2.3-HTA 2.3.5, Figure 9.32) These physical tasks are developed in detail using the HTA and are represented below.

Further, at the level of the psychological, physical/bodily changes there are automatic shifts in attention due to the task demands and automatic adjustments during physical tasks. These automatic changes could be interpreted as conscious shifts by other observers and is, thus, placed in the last level related to the interpreted value. After presenting the analysis related to CWA and WIDF the requirements generated by both these analysis is considered (Table 9.13).

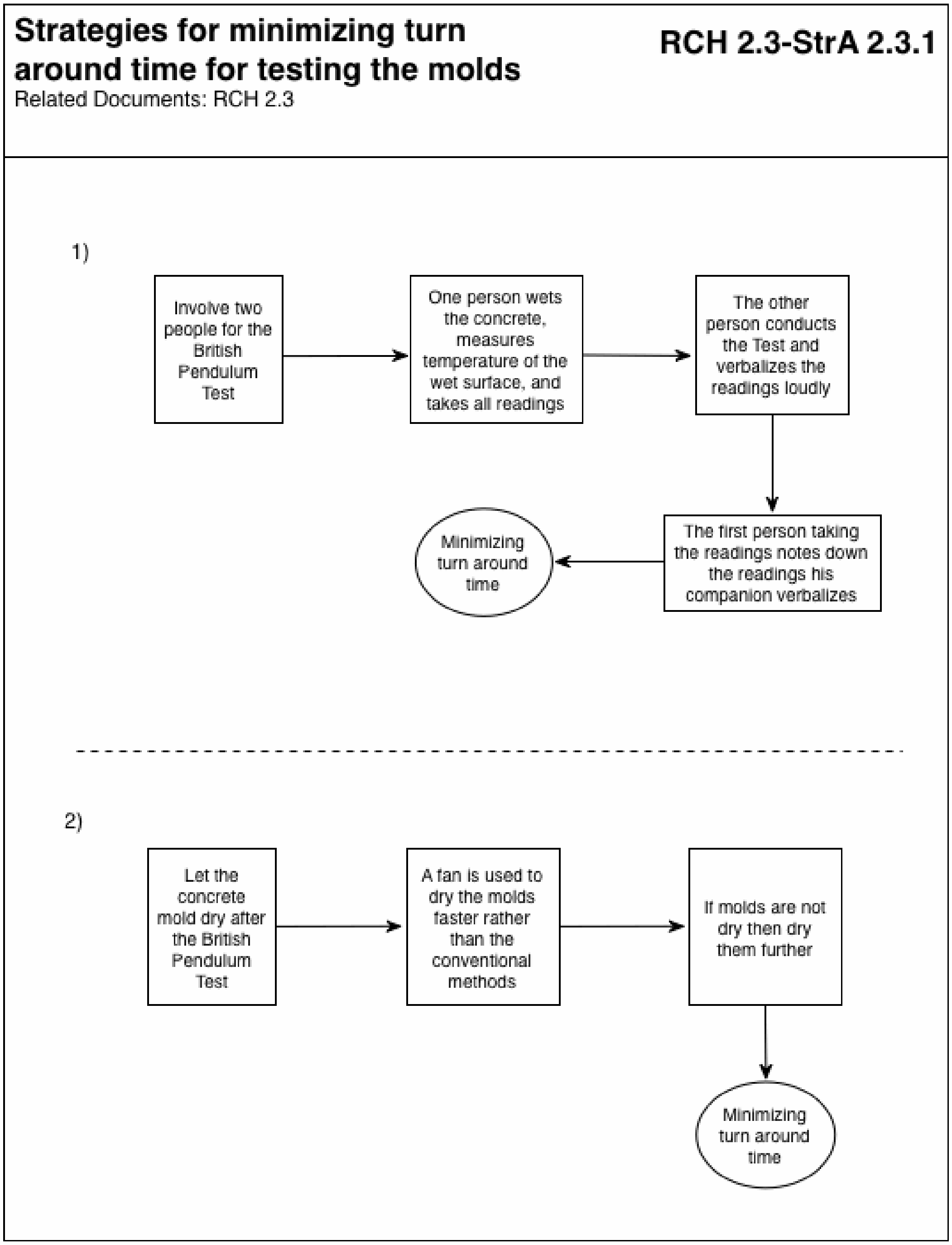


Figure 9.27: Strategies for minimizing turn around time for testing the models

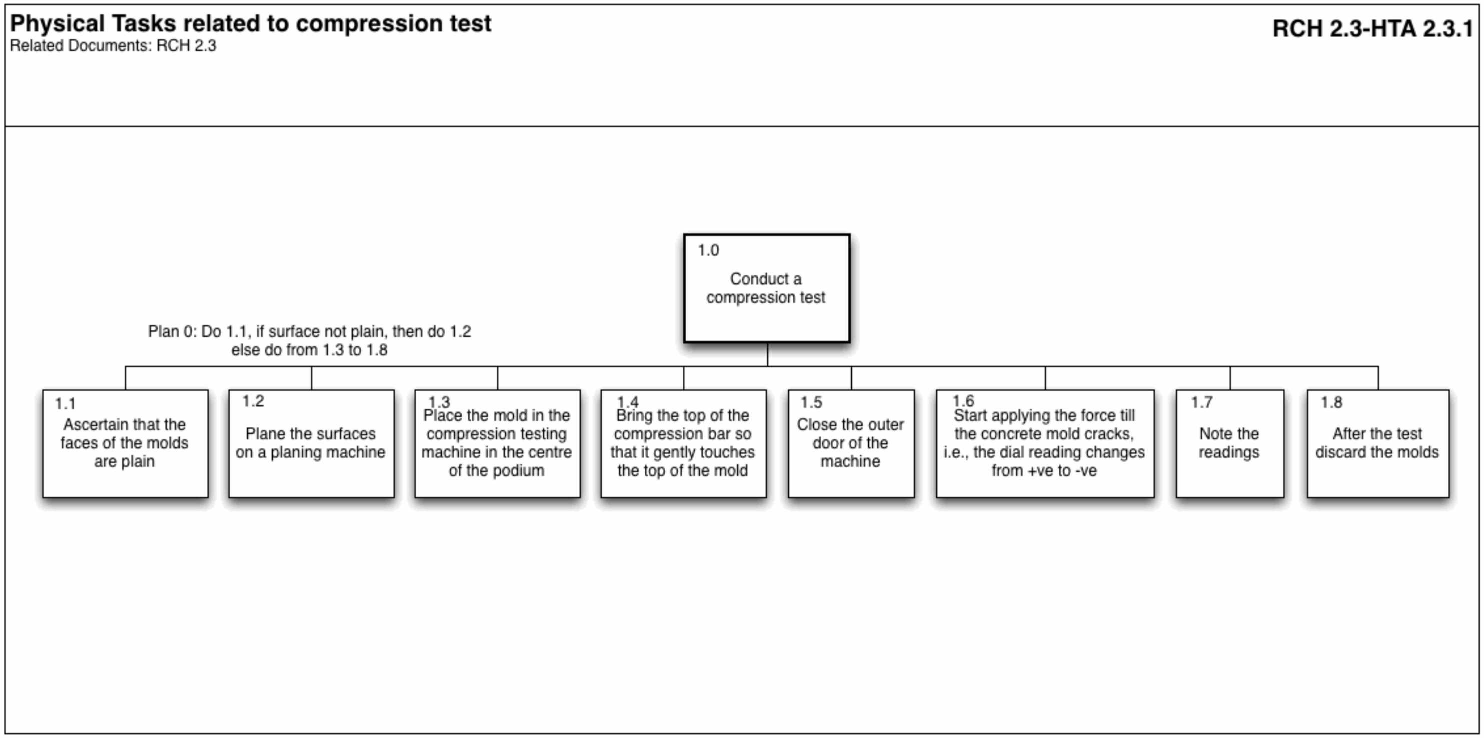


Figure 9.28: Physical tasks related to compression tests

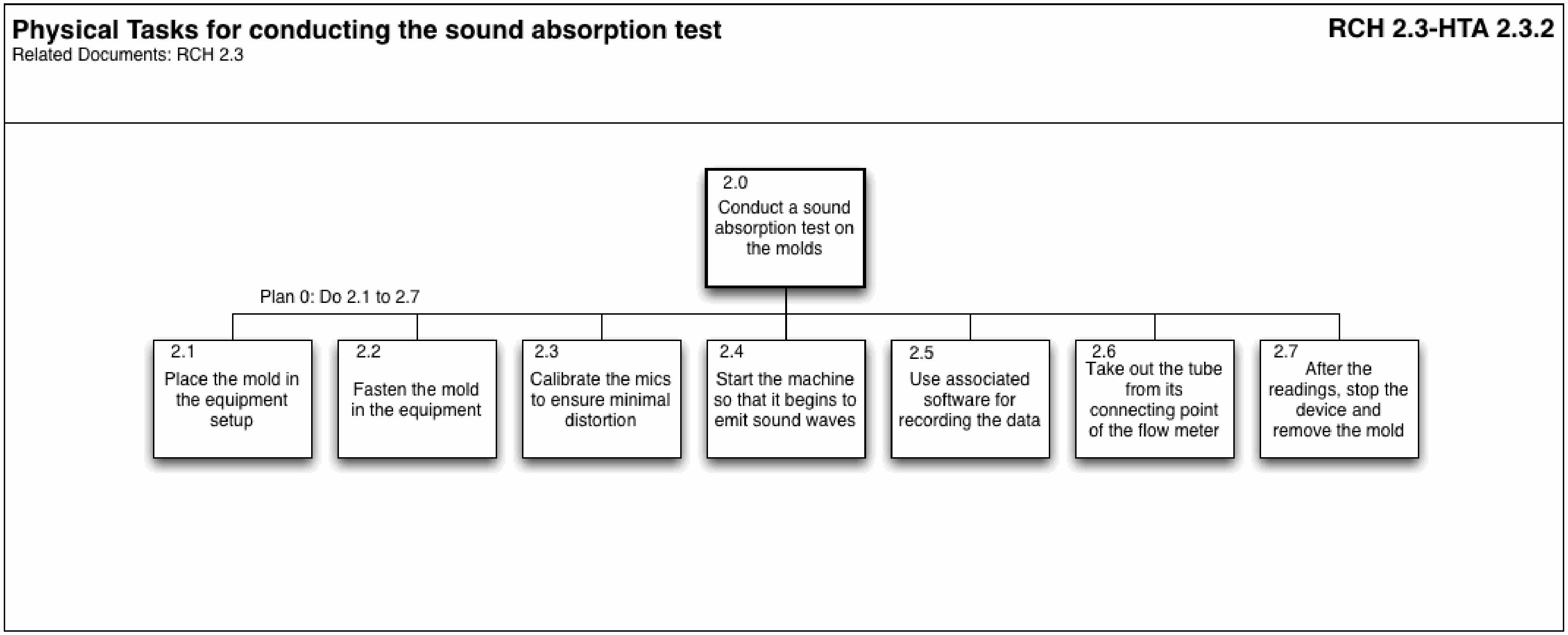


Figure 9.29: Physical Tasks related to Sound absorption test

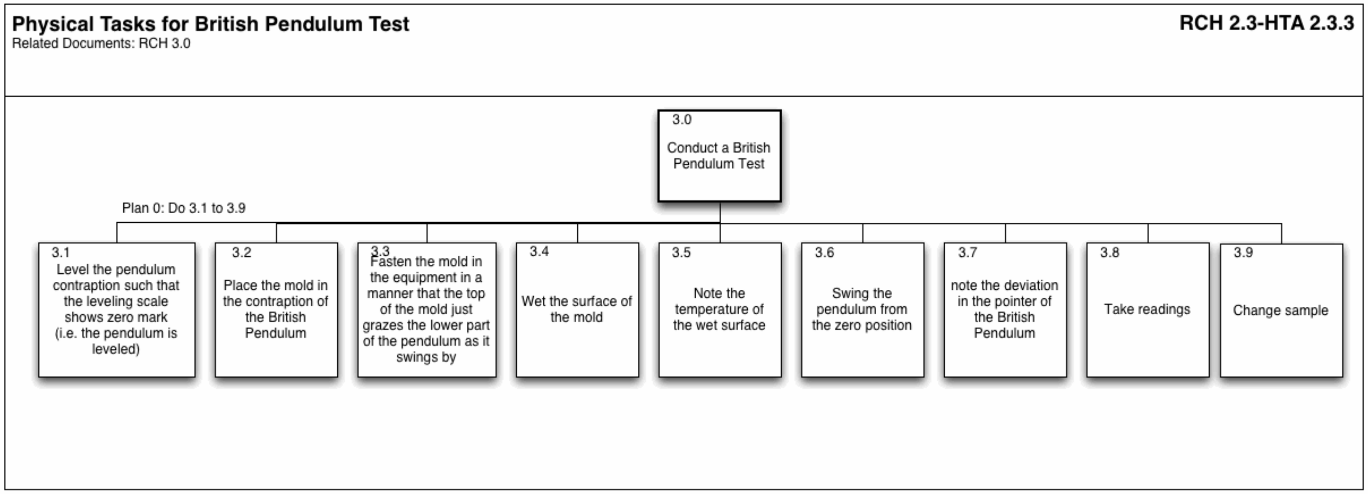


Figure 9.30: Physical tasks related to British pendulum test

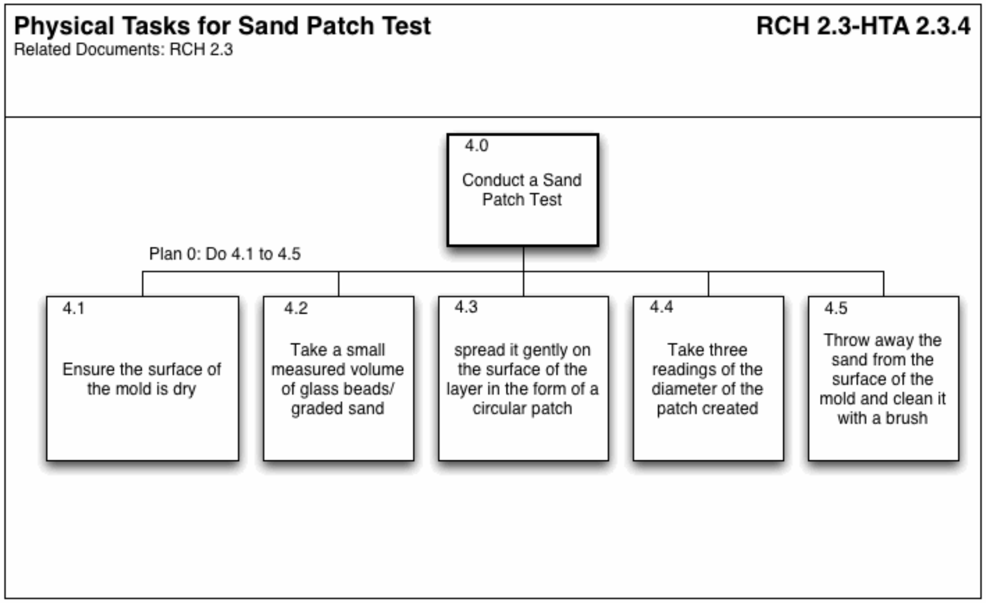


Figure 9.31: Physical tasks for Sand patch test

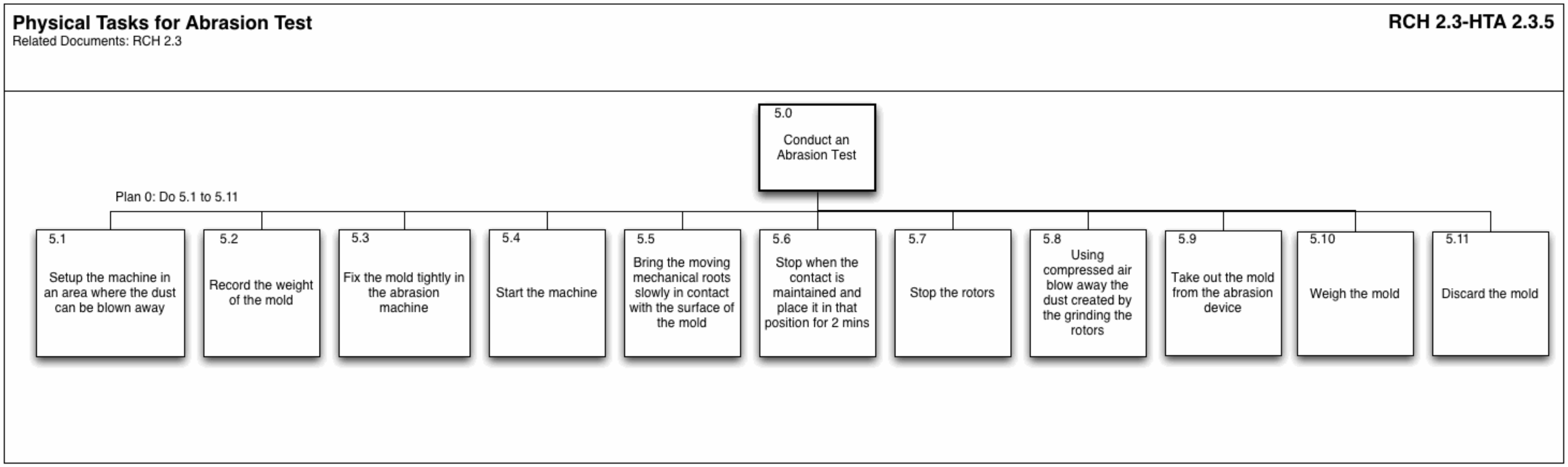


Figure 9.32: Physical tasks for Abrasion test

9.4.3 Comparison between CWA and WIDF for phase 2

Comparison between WIDF and CWA for Phase 2

	Comparison Criteria	WIDF	CWA
	RCH Environment (equivalent to AH in CWA)	Present	Present
67.	Functional Purpose	• Gather data from the samples by various tests	• Gather data from the samples by various tests
68.	Abstract Function	• Balance of scientific values and priorities related to testing of samples • Information flow through the system	• Balance of scientific values and priorities related to testing of samples • Information flow through the system
69.	Generalized Function	• Processes related to testing the concrete	• Processes related to testing the concrete
70.	Physical Function	• Compression test equipment • Sound absorption test equipment • British pendulum test equipment • Glass beads • Abrasion test equipment	• Compression test equipment • Sound absorption test equipment • British pendulum test equipment • Glass beads • Abrasion test equipment
71.	Physical Form	• Max Load: 700 kN; Measuring range: 14-700 kN • Long metal tubes for prescribed lengths, associated microphones • Standard British pendulum with standardized rubber • Standard of glass beads according to	• Max Load: 700 kN; Measuring range: 14-700 kN • Long metal tubes for prescribed lengths, associated microphones • Standard British pendulum with standardized rubber • Standard of glass

Comparison between WIDF and CWA for Phase 2			
	Comparison Criteria	**WIDF**	**CWA**
		requirements of ASTM E 965 • Standard testing machine with rotary cogs based on ASTM specifications	beads according to requirements of ASTM E 965 • Standard testing machine with rotary cogs based on ASTM specifications
72.	Use value (affordances)	• Faulty results if equipment is not used properly • Faulty results if procedures are not used properly while conducting the tests	• Faulty results if equipment is not used properly • Faulty results if procedures are not used properly while conducting the tests
	RCH for Agent	Present	Not present as a whole except for SRK
73.	Intentions/ Personal Value Structures	• Test the samples according to the tests required for the project	
74.	Abstract Information Processing / Psychological Laws/ Physical Laws	• Information processing for operating equipment and testing samples	
75.	Psychological Mechanisms	• Visual attention for testing the molds	
76.	Physiological Function	• Perceptual-Motor coordination for operating equipment and instruments during the testing process	
77.	Physical, Psychological Makeup/Anatomical form	• Proper mindfulness to assess problems leading to data recording and testing • Proper endurance for long hours of testing.	

Comparison between WIDF and CWA for Phase 2			
	Comparison Criteria	**WIDF**	**CWA**
	Capabilities (equivalent to SRK in CWA)		
78.	Skills	• Dexterity for operating equipment and conducting the tests	• Dexterity for operating equipment and conducting the tests
79.	Rules	• Rules related to using equipment correctly according to standardized procedures	• Rules related to using equipment correctly according to standardized procedures
80.	Knowledge	• Background knowledge of concrete mixing process, abstract theory related to the macro properties and the tests associated with them • Knowledge of equipment and usage	• Background knowledge of concrete mixing process, abstract theory related to the macro properties and the tests associated with them • Knowledge of equipment and usage
	RCH -Act	Present	Not present as a whole (except for Decision Ladder and Strategies Analysis)
81.	Functional Purpose	• Test the samples	
82.	Abstract information processing/ Meaning Processing Activities (equivalent to Decision Ladder in CWA)	• Information processing activities for testing	• Information processing activities for testing
83.	Generalized Strategies (equivalent strategies analysis in CWA)	• Strategies for reducing time required for testing	• Strategies for reducing time required for testing
84.	Physical Tasks	• Physical Tasks related to compression test	

Comparison between WIDF and CWA for Phase 2			
	Comparison Criteria	**WIDF**	**CWA**
		• Physical Tasks related to sound absorption test • Physical Tasks related to British pendulum test • Physical Tasks related to sand patch test • Physical Tasks related to abrasion test	
85.	Bodily/Physical changes (automatic)	• Automatic shift in attention due to task demands. • Automatic adjustments due to physical tasks	
86.	Interpreted Value	• Could be interpreted as conscious shifts; thus, provide ambiguity in partitioning the task flow for an external observer	

Table 9.13: Comparison between WIDF and CWA for Phase 2

9.5 Conclusion

In chapter 9a, the ethnography corresponding to the first step of WIDF was presented. In this current chapter, the second step of WIDF corresponding to the engineering analysis was conducted in detail. Due to the nature of the domain related to research, the system formulation identified two main phases related to the creation of the samples and the testing of the samples. These two phases of this current chapter 9 are similar to the ones identified in chapter 5. As it was described in earlier chapters 4, first the LOC devices were created and later they were tested for correct functioning. Similarly, in this chapter, first the concrete samples were created in phase 1 and then tested in phase 2. Even though, these two sites are similar in this respect, they also differ in their fundamental orientation. For example, in site 1 (chapters 4 and 5), the device was used if it did not have any debris and was functioning correctly; in contrast, in the present site, the samples were discarded after testing. In other words, the samples served an interim purpose in the nanoconcrete work domain; whereas, the fabricated device served as the goal of the LOC work domain. The corresponding analysis (models created by CWA and WIDF) conducted in sites 1 and 3 reflect these fundamental similarities and differences.

This current chapter was divided into two phases. Phase 1 consisted of creating nanoconcrete samples; whereas, phase 2 consisted of gathering data based on various tests. To demonstrate the requirements gathering capacity of WIDF, it was compared to CWA for both phases 1 and 2. The results show that due to the structure of the hierarchies of WIDF, it allows for more requirements to be gleaned from the domain under consideration.

Chapter 10: Nanotechnology in perspective

10.1 Introduction

The three research sites discussed in chapters 4-9 provided an eclectic coverage for nanotechnology. In this brief chapter, the three sites are compared to each other, to provide a holistic understanding of nanotechnology as a work domain. Further, this chapter also summarizes some of the less obvious, but still very important things I learned during my ethnographic work in nanotechnology. As it is evident from the three sites, there is no one aspect that could be a unique identifier for nanotechnology. Nanotechnology appears as devices, robotics, and materials, among others instantiations. During the ethnographic studies, two dimensions of nanotechnology emerged as salient. These dimensions include consideration of nanotechnology as a multi-faceted endeavor, along with, knowing and acting in nanotechnology settings. Finally I discuss some of the challenges and intricacies of conducting this kind of work, with a view to helping others who might like to learn about technology in a similar way.

10.2 Nanotechnology as a multifaceted endeavor

Based on ethnographic study at the three research sites, a crucial insight about nanotechnology comes into relief — nanotechnology cannot be treated as a monolithic endeavor. Nanotechnology is a field that is dynamic and in the process of coalescing. Therefore, in terms of HFE, it has to be addressed by considering of two major modes of development. First, nanotechnology is the harbinger of new products that will have a significant impact on society. Second, along with products, nanotechnology will also bring about changes in modes of knowing and acting. Both these modes of development will to be addressed by HFE in different ways. HFE professionals should addresses new products of nanotechnology in terms of new avenues for developing human technology interaction. Whereas, in case of changes brought about in existing technologies, HFE professionals should approach nanotechnology in terms of the already entrenched discipline, which will use nanotechnology products. This distinction in approaching nanotechnology was made clear by the three research sites. In site 1 and 2, nanotechnology was approached in terms of challenges posed by a new technology *qua* nanotechnology. In contrast, in Site 3, nanotechnology was approached in terms of the challenges posed by the already existing overarching discipline of civil engineering. Further, nanotechnology as a multi-faceted endeavor can be developed in terms of three main insights gained from the studies: Technologies of new as compared to the old; Multitudes of perspectives; Devices and materials in nanotechnology.

10.2.1 Concept of Nanotechnology

The word nanotechnology is a compound made of the words “nano” and “technology”. Technically, the prefix nano refers to the factor of 10^{-9} in the metric system. However, in actual practice the order proves to be a misnomer. As the field studies showed in practice, the actual order (nano- or micro-) was not of key concern, as nanocomponents are often used in devices which have micro components. Even though, strictly speaking, the researchers may be doing microtechnology, the actual activity tended to diffuse between the orders of magnitude. For our purposes, the working definition of nano included the small scale, often unable to be viewed by the naked eye: both micro and nano. After the prefix, the word technology posed a problem. Typically, the common usage of the word technology refers to things. However, this usage often conceals more than it actually denotes the true character of technology. Technology as a term does not necessarily have to be focused on objects; in fact, viewing technology as a keyword from multiple vantage points allows for an in-depth treatment of our area of nanotechnology (for e.g. see Mitcham, 1994, Prus & Mitchell, 2009). Therefore, the ethnographic venture was conducted with the following viewpoint: *nanotechnology is a situated endeavor of human knowing and acting*. Nanotechnology is understood both from an active, agentic-point of view as well as an engineering based point of view. Both have been taken together to understand nanotechnology and HFE in this thesis. A related salient aspect was the manner in which the subject matter was approached; i.e., even though the focus of this thesis is on engineering, while approaching fieldwork in nanotechnology, no *a priori* classifications were made. Rigid labeling and categorization were strictly avoided. The classifications and concepts were strictly obtained from the fieldwork data from the three research sites. The perspective between engineering and symbolic interactionism were taken together to comprehend the holistic understanding of nanotechnology in the three sites.

10.2.2 Technologies of the new as compared to the old

The standard image of nanotechnology is that of a field which will bring about changes by incorporating novel devices and materials. These changes are expected to bring about enhanced and more efficient technologies that will be used for the betterment of society. In contrast to the view of nanotechnology as bringing forth novel technologies, a different view should also be considered; i.e., how does nanotechnology affect the technologies of the old. In Site 2, this aspect of nanotechnology was made clear by consideration of civil engineering. This branch of engineering is one of the oldest of engineering professions. Further, the material concrete is also quite old and widespread. It is also one of the most consumed products, after water, by human kind. The research in site 2 showed that nanotechnology will change the already existing technologies, such as concrete, but will do so in a manner by which nanomaterials will be used under the banner of the already existing disciplinary field. In other words, nanotechnology per se will be folded into the identity of the already existing disciplinary field. In terms of Site 2, the civil engineers are not conducting nanotechnology research per se; rather, they are using nanomaterials to further their own disciplinary research agenda. Therefore, while considering nanotechnology, both the old and the new have to be addressed together to comprehend the changes nanotechnology is expected to bring to society.

10.2.3 Multitude of perspectives

In considering nanotechnology research as a multifaceted endeavor, the variety of actors need to be addressed. In the three research sites there were two main group of students involved in nanotechnology settings — graduates and undergraduates. Graduates students have the goal of conducting research as a part of their PhD requirements and pushing the boundaries of nanotechnology as a field. Typically, their research is supported by the lab to which they belong. Thus, the theatre of operations for graduate students are constrained by the demands of the university academic supervisors and nanotechnology as a research field. In contrast to the graduate students, the undergraduate students of UWNRG were making robots for a competition. Since these students do not have a readymade matrix in which to embed their theatre of operations, they literally create this overarching matrix along with the competition robots. Not surprisingly, the UWNRG undergraduate students, not only have technical and control teams for addressing the technical challenges in robot navigation, but also have a business development and marketing team for fund raising and maintaining presence in the UW community. Further, the aim of UWNRG undergraduate students, in contrast to the graduate students of the other two sites, is not to conduct research per se; rather, their aim is to win robotic competitions. Research is only one aspect of this overarching process. Therefore, in considering nanotechnology as a multi-faceted endeavor the various groups and their orientations have to be addressed in order to understand the concept of nanotechnology in a well-rounded manner.

10.2.4 Devices and materials in nanotechnology

In terms of considering nanotechnology as a multifaceted endeavor, the distinctions between the various instantiations of nanotechnology should be addressed. In this study, nanotechnology was studied in terms of three instantiations - Devices; Robotics (“active” devices); and materials. In the creation of the device, the device is typically, considered as a stand-alone entity having a separate identity. In contrast when the material is used, it is characterized in terms of the matrix of the surrounding materials; i.e., how the macroscale properties of the material are changed due to the addition of the nanomaterials. In other words, in case of devices, nanotechnology was instantiated as things in themselves; whereas, in the case of materials, nanotechnology was instantiated in terms of the surround. Such a situation demonstrates that it is difficult to characterize nanotechnology in terms of any standard “method” or a “body of knowledge”. Rather, the manner of development of nanotechnology is varied and are to be considered in terms of the materials coupled with the goals of the people involved in the research.

10.3 Nanotechnology research in terms of knowing and acting

Along with Nanotechnology as multi-faceted endeavor, HFE should take into account the tacit knowing and acting involved in nanotechnology research settings. Typically, nanotechnology is depicted as advanced knowledge with a scientific and mathematical outlook. This image of nanotechnology obscures the tacit knowing and acting that plays an important role in research settings. As shown in Site 1 and 3, the tacit knowing and acting, as well as, dexterity contribute heavily towards the workmanship for making the chips and molds. Along with the tacit knowing and acting, knowledge of instruments is key to development of nanotechnology as a discipline. Researchers, typically, have a vast knowledge base about the kinds of equipment that would help in producing intended outcomes. As demonstrated explicitly in site 1 and 2, knowledge of equipment (thing knowledge) was a key aspect of nanotechnology settings. Along with the tacit knowing and acting, thing knowledge is a hidden dimension of knowledge that pervades nanotechnology research. In terms of HFE research, HFE professionals should account for the thing knowledge as well as tacit knowing and acting in nanotechnology research.

10.4 Research Processes, Problematics, and Suggestions for Future Researchers

10.4.1 Initial Contacts and Access

The solicitation for the ethnographic project started with a series of “Cold Calls”. “Cold Call” is a term commonly used in sales parlance, where the salespeople present themselves to prospective clients (Prus, 1997, p. 221). To initiate contact, multiple emails were sent to the lab directors (professors) associated with nanotechnology at the University of Waterloo. Out of the multiple emails, one lab director kindly allowed access to the lab premises (site 1). This was due to the fact that the person was acquainted with my PhD supervisor. Since the area of research was to understand how graduate researchers work in nanotechnology settings, it became obvious that access to labs, at a high profile university such as Waterloo, could only be possible if the officials in charge were sufficiently at ease about my background. Apart from the “cold call” approach, introductions and personal connections were sought. I asked graduate students in areas of nanotechnology, as well as other acquaintances to put me in touch with students or their lab directors. The reliance on the good graces of people (at times complete strangers) for introductions was a key aspect of the project.

As my study evolved, I found it necessary to understand nanotechnology from a broader perspective. In this endeavor, senior members of the UW Nanotechnology Robotics (UWNRG) were extremely supportive and helpful in providing access to their activities. Without their acceptance, the study on site 2 would not have been possible. Further, a friend, MGH, was instrumental in broadening my horizons on nanotechnology. He was incredibly helpful in introducing me to the world of concrete pavements. Without his help, the study on site 3 would not have been possible. Similar to site 1, in site 3, the professor (MGH’s supervisor) in charge of the pavement lab was acquainted with my PhD supervisor. The acquaintance helped to clinch the access to research work in concrete pavements.

Apart from these research sites that were finalized, there were also two dead ends. In the first case, a professor, in reply to my “cold call”, had introduced me to his postdoctoral fellow. The postdoctoral fellow was to serve as the point of contact. However, after about three weeks, I started to realize that I could not obtain the necessary depth of inquiry – matters did not gel and the “magic of encountering the other” did not quite work out in this setting. Therefore, I found it prudent to curtail my line of enquiry at this lab. After duly thanking them for their gesture of allowing me access to their lab, the professor and the postdoctoral fellow were informed that due to certain changes in my research design, I had to rethink my approach and therefore, I would discontinue with the observation.

Along with the first case, a second lead proved as a dead end for different set of reasons. My supervisor had introduced me to a professor for access to his laboratory, to which the professor kindly agreed. However, most of the fabrication of devices was conducted in a clean room facility. The lab manager of this clean room facility did not allow me the access to resources. This potential research site, as the previous one, proved as a dead end because of the secondary gatekeepers. In getting research access, one can encounter resistance from multiple gatekeepers, not all of them being primary. Relatedly, even if there is research access, there is no specific guarantee that every potential site will provide the same depth of information as the others.

10.4.2 Observation on Fieldwork Methods

To ensure a proper breadth for the concept of nanotechnology, three far flung areas were chosen: devices, robotics and materials. Apart from these standard distinctions, it was also ensured that there were overlaps and disjunctions. Site 1 focused on LOC devices that are an increasingly important area of research in nanotechnology. The director of the lab site 1 is affiliated to the UW Nanotechnology program. Similarly, the UWNRG team in site 2 had nanotechnology professors as mentors. Sites 1 and 2 were primarily chosen in areas that lay under the purview of the official description of nanotechnology at Waterloo. In contrast, site 3 dealt with the study of nanomaterials in concrete pavements, an application in civil engineering. Thus, along with official descriptions, non-officials descriptions were provided for a comprehensive coverage of nanotechnology. Further, the first site dealing with devices focused on graduate students; similarly, in site 3, graduate students were also the main participants. In contrast to sites 1 and 3, site 2 focused on undergraduate students. Since the site 1 and 3 comprised of graduate students, the focus of activity was publishing research work or completing their PhD programs. In contrast, in case of site 2 the primary goal was winning in the robotics competition.

Since the research was conducted at cutting-edge research facilities, the sensitivity of information gathered is to be noted. Therefore, the main focus in this study was to provide a generic understanding of how these aforementioned nanotechnology settings operate. Specific details of individual research work of the participants were not mentioned. Participation was completely voluntary and informed consent was received from all individual participants of sites 1 and 3, whose work was followed very closely. In site 2, consent was received from the UWNRG director. Since this consent was based on the discussion that the director had with the UWNRG group as a whole (general democratic consensus), individual consent was not taken.

In all, the total number of *formal* hours spent in fieldwork amounted to 247 hours in all (site 1: 94 hrs; site 2: 50 hrs 45 mins; site 3: 102 hours), details provided below. Further, the number of participants varied based on the area of endeavor for each site. Since sites 1 and 3 were connected with close observations of the actual activity in the lab, the number of participants in these sites was smaller. In contrast, in site 2, where the whole UWNRG undergraduate group was studied, the number of participants was greater. Apart from the participants in these three sites, many interviews were initially conducted in the broader academic community of UW graduate students, to get a generic understanding of the field of nanotechnology. The insights gained from these interviews were used to converge onto the final three research sites.

Observation and interviews were the primary methods adopted in this ethnographic study. Along with these two methods, I also relied on contextual information - informal conversations and simply “hanging out” with the participants. To gain a better understanding of methods, I reviewed work procedures in site 1. Whereas, in site 3, I read a student’s PhD proposal and related literature pertaining to lab activities in concrete testing to get an overall sense. Most of the crucial insights that I received were when the participants were sufficiently relaxed — from informal conversations over lunch or break time. “Hanging out” and listening to discussions also proved to be very useful as it provided an understanding of the context in which the participants approached their work.

10.4.3 "Fitting in" and Dynamics of data gathering

The task of “fitting in” was a two-way process involving both the participant-other as well as myself. The three research sites demanded different approaches. Site 1 was based largely on following individual participants. Therefore, after getting the permission from the lab director, I individually contacted the members. Graduate students in site 1 adopted a favorable attitude towards me and were willing to show me the inner workings of LOC technology as well as discuss microfluidics in general. The beginning phase of the project at site 1 was awkward. However, as the participants and I spent long hours in the lab, a sense of camaraderie arose. Research in LOC technology is an arduous process that can be often frustrating. At times, the emotional process involved in research produced strange and absurd situations. After spending hours to make the chips and then spending another countless hours in finding that the none of them worked is an extremely taxing situation that exposes the vulnerability, as well as the complex aspects of the participants — at times, the mean streaks of the researchers were displayed. However, overall the long hours of observation, explained the challenges that the participants faced in their everyday research. Since site 1 comprised more of individual work schedules depended on the participants, sometimes the scheduled hours could often be late hours in the evenings or early in the mornings. This proved extremely taxing for me over the duration of data gathering at site 1.

In research site 2, there was an initial phase of interviews that was required to gain an overall understanding of the people with whom further contacts were to be established. This establishing of contacts was compounded by three aspects of the scenario. The initial process of gaining an understanding of the group was rife with ambiguities. First, the website, based on which contacts were emailed, had not been updated for quite some time. Second, the group was in a process of being restructured. Third, the decision to observe the group was a democratic process (as I later came to know) and there was a need for establishing my credibility before I could pursue my research with the group. Only in August, 2013, after considerable ambiguity, I could make the decision of following this group more closely. However, once I started attending the meetings, the members of group showed immense support. Since the group was composed of undergraduate students, a byproduct of conducting research in site 2 was gaining an understanding of University of Waterloo engineering undergraduate subculture of nerf guns, zombies and the like.

In contrast to the above two sites, in terms of participants and timings, site 3 posed a lesser challenge, due to MGH coordinating and making introductions. A crucial aspect in this site was that not only was the material nanosilica embedded in the overarching concrete matrix but also, more broadly, the field of nanotechnology was subsumed under the approach of civil engineering. This understanding, which emerged as the study progressed, provided a major hurdle initially. In short, I understood how civil engineering functioned. This insight that nanotechnology, when applied to already existing disciplines, may end up being subsumed under the disciplinary matrix of that particular field of knowledge, was a crucial aspect in providing a comprehensive understanding of nanotechnology. In this site, during one or two sessions, due to the absence of participants, I ended up as acting as a helper. Thus, this site changed my role from observer (in sites 1 and 2) to participant-observer for part of the project duration. Another key insight gained in this third site was that in order to understand concrete, I had to understand it also from the perspective of what it is not. This perspective of the other-material was provided by researchers working with asphalt in pavement engineering. Asphalt provided a suitable foil to understand concrete. Even though discussions of asphalt have not been developed in this study, the asphalt researchers provided an invaluable insight into concrete as a material.

In each of the three sites, I followed a two-step process to make sense of the context. First, I tried to glean as much as possible from the situation and form a general understanding. As the project continued, I adopted a reflexive approach to understand how the new instances fit into my generalized understanding. This two-step approach was a flexible ongoing process rather than a strict categorical injunction. Moreover, after the chapters pertaining to each site were completed, they were given to participants from each of those sites to ensure the details were veridically represented. Only after the participants had provided the feedback regarding the written ethnography, were the ethnographic reports consolidated into the thesis.

10.4.4 Directions for future engagements between interactionist and engineering viewpoints

Over the duration of this nanotechnology project and the thesis I learnt that to address human life we have to consider the basics of human lived experience from the point of view of the actors themselves. Human life is multiperspectival, reflective, activity-based, negotiable, relational and process-based. Therefore, to understand human life we have to adopt a means that provides us an intimate familiarity with the subject matter. Ethnographic research and considering human life in terms of processes allows for an understanding of the meanings that people have for their surroundings. It also helps us to account for the changes in meanings and the interpretive process used in the changes in meanings. These basics of addressing human life provided me with a new conceptual and methodological approach for addressing human life in the making. Thus, the interactionist viewpoint provided a set of concepts and practical approach for addressing the ongoing nature of group life.

The next step was to recognize that the interactionist approach had to be integrated with other approaches from activity theory, ecological psychology and engineering based approaches. This was done by addressing the basic assumptions of all the above approaches and then approaching nanotechnology settings. In terms of the settings, I found that to address nanotechnology as a human engaged endeavor, we have to begin from the perspective that technology is a social process. I learnt that by addressing this aspect allowed for a richer view of the meaning *in* and and *of* activities allows for a trans-contextual comparison between sites. Therefore, as pointed out earlier in this chapter, Site 1 and Site 3 are similar because of the workmanship present in these two circumstances. However, they also differ because site 1 involved more amount of risk in creating the end product as compared to site 3. Thus, this type of comparison helped to provide a broader perspective on nanotechnology.

At the same time, the interactionist viewpoint had to be understood along with the engineering viewpoint to form a clear view of how technology as a humanly engaged process could be used to provide an insight for engineers. Currently, these challenges are slowly coming to the forefront with HCI theorists turning towards sociological approaches for systems design. My thesis is also a step in this general direction. However, I have tried to balance both the interactionist approach and the engineering approach. It is to be noted that in contrast to the interactionist approach, which emphasizes technology as process, engineering approaches also have to take into account technology as objects, artifacts and systems, together with design notions of function-structure linkage, correct function and malfunction. Therefore, in the future, engineering should aim to balance these two viewpoints to provide a detailed understanding of the work domain as well as the requirements for systems design. To conclude, I have three main suggestions for future researchers that emerged from my fieldwork and thesis. First, technology can be approached from the viewpoint of interactionist research for a richer understanding in terms of humanly engaged endeavor. Second, understanding technology in terms of activities and processes allows for a comparison between research sites for a nuanced view and a generic understanding. Finally, and more crucially, the understanding gained from the interactionist view is not enough for systems design. The understanding of technology gained from the interactionist viewpoint has to be balanced with the engineering viewpoint for systems design.

10.5 Conclusion

Chapters 4-9 presented a glimpse of nanotechnology in terms of devices, robotics and materials. These research areas are not exhaustive as nanotechnology appears in various instantiations. Nanotechnology can be best considered as a *mélange* of multiple perspectives under a single banner. From a disciplinary perspective, it is often divided into a variety of categories such nano-bio systems, nano-electromagnetic systems, among others. Notwithstanding these various demarcations and subdivisions, the aim of this thesis was to address nanotechnology from a broader vantage point for HFE research. Along with the above areas, the chapters in this section (Chap 5, 7 and 9) also presented models based on WIDF and CWA. The design requirements, elicited from both these set of models were compared to each other. In all the three cases, due to its structure, the extended CWA presented more design requirements as compared to the traditional CWA.

Chapter 11: Conclusion—Summary and further research

11.1 Introduction

This chapter presents the conclusion to this thesis. It provides a brief summary, important contributions, limitations, and directions for future research. The main aim of this thesis was to extend CWA for providing interface design requirements for the embodied, embedded and socially situated dimensions of human conduct. Therefore, this thesis presented a systemic and systematic engineering framework (WIDF) for requirements gathering that addresses human-technology interaction in terms of a naturalistic mode involving embodiment and embeddedness in a socio-technical milieu.

To this end, in Chapter 2 there was a discussion of CWA and its background literature. CWA was situated in the broader themes in HFE and HCI pertaining to human-technology interaction. These themes were used to identify possibilities that could serve as the basis for extending CWA. Based on these themes, in chapter 3, the extended CWA was presented. The extended CWA derives from the following major theorists—Gibson (psychology); Bernstein (motor control); Blumer (sociology); and Rasmussen and Vicente (engineering). Using these insights about human knowing and acting presented by these above theorists, WIDF is constructed as a two-step framework. The first step consists of an ethnographic study based on symbolic interactionism (Blumer); while the second consists of engineering models based on Rasmussen's approach. Both these steps take into account the underlying notions of embodiment (Bernstein) and embeddedness (Gibson) for systems design.

Further, in order to demonstrate the applicability of the extended CWA in comparison with the traditional CWA, it was used in nanotechnology settings. Nanotechnology is a new endeavor for HFE, and there are very few empirical studies conducted in this area. Therefore, three research sites pertaining to devices (chapters 4,5), robotics (chapters 6,7) and materials (chapters 8,9) were addressed to provide a generalized understanding of nanotechnology. In each site, first the ethnographic study was presented (e.g., Ch, 4 presented the ethnographic study for Site 1) followed by an engineering analysis in the next chapter (e.g., Ch. 5 presented the models related to CWA and extended CWA). After these three sites, a discussion of the major themes found in these research sites were addressed in terms of a generalized understanding of this work domain. Further, research problematics in dealing with nanotechnology were also briefly discussed to provide possible directions for future researchers addressing this new work domain.

11.2 Significant and original outcomes of research

Based on the research conducted as part of this thesis, there are two significant and original contributions. These include extending CWA for gathering design requirements for embodied, embedded and socially situated aspects of human knowing and acting, as well as conducting an empirical study of nanotechnology as a novel work domain.

11.2.1 Contribution 1—Extending CWA for addressing the embodied, embedded and socially situated aspects of human knowing and acting

The first contribution is extending CWA in terms of WIDF for gathering design requirements for novel human technology interaction. The NBIC convergence has brought about a growth of novel technologies and pervasive computing resulting in “smart” and “intelligent” environments. As a result, human interaction has become more naturalistic in nature. Designing interfaces for these systems will require addressing the embodied and embedded dimension of human behavior. WIDF is constructed as a systemic and systematic framework that will allow for addressing this embodied, embedded and situated dimension of human conduct. In particular, along with extending the abstraction hierarchy, WIDF provides two new hierarchies pertaining to the body and the acts. Further, it also links the three hierarchies through new layers, providing a tight interconnection between the person, acts and environment. These aspects have practical consequences in gathering design requirements. For example, in site 1 (devices) and site 3 (materials), the role of the body, dexterity and workmanship in activity was a crucial aspect of these domains. While designing technology for lab activities, these aspects become of paramount importance. In site 1 and 3, there was an explicit need for addressing the aspects of workmanship and the body in relation to the device and samples. Thus in terms of design, by supporting the body and the workmanship, it is possible to improve the quality of the devices and samples and to reduce the risk involved in producing them. While using CWA these aspects of the domain was not completely captured; however, WIDF addressed these aspects. Further, in site 2 (robotics), the sociotechnical nature of the work domain required a detailed consideration of the socially situated activities involved in the work domain. WIDF with its detailed consideration of activities allowed for gathering nuanced requirements from Site 2. These requirements can be used to design devices and procedures to support the socially situated aspects of work. Thus, in general, WIDF extends CWA for embodied, embedded and socially situated aspects of human knowing and acting in novel work domains.

11.2.2 Contribution 2—Nanotechnology and HFE

The second contribution is providing an empirical study of nanotechnology. Currently, HFE theorists have stressed the need for engaging nanotechnology; however, detailed empirical studies are yet to be conducted. Thus, this thesis provides an empirical foray into nanotechnology in terms of devices, robotics and materials. By taking these three aspects of nanotechnology into account, this thesis provides a broader vantage point for viewing nanotechnology. Thus, nanotechnology is not only viewed in terms of a future-based technology (LOCs, robots), but also in terms of technologies of the old (concrete). To fully comprehend the potential of nanotechnology, HFE should take into account the various ways in which nanotechnology will have an impact on society. This thesis provides the first step towards a more comprehensive construal of nanotechnology in HFE.

11.3 Limitations

Along with the contributions presented by this thesis, there is one main limitation. Currently, support for teams and groups have not been provided for in WIDF modeling. This limitation is due to lack of time rather than any inherent theoretical limitations of this thesis. In the present three scenarios pertaining to the three research sites, teams and groups have not been specifically modeled in WIDF. This is mainly because of the following reason. Team and groups involve negotiations and boundaries that present challenges in terms of in-group and out-group behavior. These dimensions of in-group and out-group behavior not only change the ways of knowing and acting but also have a significant effect on modeling of the domain under consideration. Thus, to present models for teams and groups demands a detailed study of the interaction of groups, as well as an understanding of how group interactions can be categorically modeled. In the future, this dimension of teams and groups will be addressed in detail for WIDF.

11.4 Directions for future research

Based on the topics addressed and the results of this thesis, there are five major areas for future research that will prove fruitful for HFE. First, a primary aspect of this thesis was that it extended the role of the body in CWA. Thus, this step allows for the broader understanding of the human in HFE. Specifically, the requirements derived from the extended CWA (WIDF) can be extended with the traditional tools of physical ergonomics, such as REBA, RULA, among others. This need for providing a rounded view (physical and cognitive) of HFE in terms of new tools and frameworks requires further research.

Second, the traditional CWA uses means-ends as a central aspect of relations between levels. In contrast, the extension of CWA uses reasons and causes for structuring the hierarchy. Therefore, further research is needed to theoretically connect means-ends links with the new hierarchies relating to the person (RCH_P) and acts (RCH_A). More broadly, the use of means-ends reasoning or practical reasoning should be understood in terms of design thinking for systems.

Third, in Chapter 2 on CWA it was highlighted that the traditional CWA required formal techniques for assessing the empirical impact of the obtained solutions. Also, there should be measures that can be used to gauge the proposed method in terms of generic aspects of learnability, ease of use and deployment, among others factors to show how the proposed method is easy or difficult to use in light of established methods. The need for formal techniques for evaluation becomes necessary for the extension of CWA (WIDF). This thesis highlighted the engineering epistemological orientation on which CWA rests. Thus, it is possible to measure the empirical impact of solutions obtained for extended CWA by employing formal tools already present for assessing engineering systems, as well as understanding the impact in terms of overall systems design and their optimized performance.

Fourth, there is a need for extending WIDF in terms of teams and groups as well as designing for phenomena of interpersonal behavior and group behavior, in general. Further, in viewing the extended CWA (WIDF) as a systemic framework, it should be connected to other entities that shape human knowing and acting, such as, organizations and institutions.

Finally, nanotechnology is a new area for HFE research. Currently, there is a lack of empirical research pertaining to HFE and nanotechnology. For addressing nanotechnology comprehensively, HFE should address the various dimensions in a significant manner. This thesis has identified varied areas that are engaged with nanotechnology in some significant manner. More empirical studies are required for characterizing nanotechnology in a comprehensive manner to search for new avenues and possibilities for engagement with HFE research.

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