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Title: Pre-Prototyping Framework: An Early Design Prototyping Methodology for Human-Centered Products and Workplaces

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Prototyping is a crucial step in product design and development, but it is also known as the highest sunk cost. The top 20 Research and Development (R&D) department spends 142 billion dollars, yet 40 to 46 percent of this money goes into developing products that cannot even make to the market. Furthermore, the lack of comprehensive and widely accepted prototyping strategies and guidelines challenges the success of design teams in selecting options among a plethora of prototyping methodologies, techniques, and resources. The first shortcoming of current prototyping strategies is that they focus on the prototyping experience or the hands-on prototyping process without paying adequate attention to theoretical guidelines about prototyping factors and theories. The second limitation is the sparse guidelines of practical 'know-how' or what tools to use while building the prototype. The third shortcoming is that the existing prototyping strategies

do not adequately incorporate the Human Factor Engineering (HFE) guidelines into the design of human-centered products. To address these shortcomings, this dissertation aims to formulate a Pre-Prototyping framework that aids designers in exploring prototyping strategies for human-centered products during the early design process.

The overall objectives of this study are split into primary and secondary research objectives. Three secondary objectives are developed as building blocks of the overarching research objectives. First of all, Chapter 2 addresses the first secondary research objective by exploring how Performance Shaping Factors (PSFs) affect human performance and what prototyping strategies should be employed to capture it. Next, Chapter 3 addresses the second secondary research objective by proposing a computational prototyping method, which assists the designer in exploring the design space to integrate HFE design principles in the conceptual design process. Finally, the third secondary research objective is presented in Chapter 5, which explores the levels of human product interaction and the fidelity that plays a role in prototyping strategies. The secondary research objectives helped to gain deeper insight into prototyping for HCD based products. These insights are building blocks to address the three primary research questions and develop the Pre-Prototyping framework. The methodology to develop the Pre-Prototyping framework follows a similar step-by-step approach and workflows common to other prototyping frameworks in the prototyping literature; however, the proposed Pre-Prototyping framework adds HCD guidelines and proactive prototyping strategies by injecting HFE design principles. The distinction between this work and the existing prototyping framework is that the focus is on a Pre-Prototyping strategy rather than a hands-on prototyping activity. The second distinction is that this prototyping methodology is developed by focusing on the human-centered design since most of the existing methodologies concentrate solely on the prototyping experience.

The proposed methodology comprises Prototyping Categories, Prototyping Dimensions, and Prototyping Toolbox along with Human Factor Guidelines. These different areas are combined in a framework that is currently presented using MS Excel User-Form. Designers can use this framework via Excel User-Form to conceptualize Pre-Prototyping strategies based on the specific HCD requirements. The proposed methodology is validated by an experiment that conducts 12 prototyping problems between the Intervention group and the Control group. Independent t-tests are be performed between the two groups. It is found that participants who use the proposed framework develop better Pre-Prototyping strategies than those who do not. In addition to the quantitative test, qualitative analysis is carried out by capturing the prototyping experience and attitude of the designers. Likert Scale and screen recordings data are used to gain further insight into participants' evaluation of the framework. It is discovered that the participants perceived the Pre-Prototyping framework to be helpful and they agree to use the Pre-Prototyping framework for prototyping human-centered products.

Pre-Prototyping Framework: An Early Design Prototyping Methodology for Human-Centered Products and Workplaces

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Salman Ahmed, Author

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

Table | Page

LIST OF APPENDIX FIGURES

LIST OF APPENDIX TABLES

Chapter 1: Introduction

1.1 Overall Research Goal

This research aims to formulate a Pre-Prototyping framework that aids designers in exploring prototyping strategies during the early design. Unlike other prototyping studies, the framework proposed in this research focuses on the design and analysis of human-centered products and workplaces by integrating prototyping theories and technologies with human factors engineering (HFE) principles. The prototyping strategies consist of a set of design decisions that dictate what theoretical approaches and technology tools need to be considered before the actual prototyping activities start.

1.2 Motivation

Prototyping is one of the most critical aspects of new product development or improving existing products [231]. The top 20 companies that are known for their innovative products spend around 142 billion dollars in their research and development (R&D) departments. However, it is found that around 40 to 46 percent of resources are spent on products that do not even go to the market [66]. For example, it took about 5,127 prototypes and five years for Dyson to come up with the most successful vacuums on the market [129]. Prototyping is the highest sunk cost in the product development process [54]. However, in the current prototyping literature, there is a lack of comprehensive and widely accepted prototyping methodology [54, 166]. The current prototyping methodologies focus mainly on prototyping activity or hands-on prototyping experience. Most of the existing prototyping methodologies rely on designers' intuition or experience in building a prototype rather than providing systematic guidelines and prototyping best practices to aid designers in their prototyping quest [144,166]. Another shortcoming of the existing prototyping methodologies is the lack of fabrication guidelines. The absence of fabrication guidelines regarding what tools and technologies to use to build a prototype causes wide variation in the prototype quality even though when the designers use the same prototyping methods [166].

Another limitation of the current prototyping methodologies is that Human Factor Engineering (HFE) guidelines are not adequately considered [166]. The absence or partial consideration of HFE guidelines causes products or workspaces that do not address human needs and limitations. HFE is a multidisciplinary domain that applies theory and practice to optimize human well-being and overall system performance [103,134]. It aims to reduce human error, increase productivity, and enhance safety and comfort by applying theory and practice from a wide range of disciplines to design and evaluate products, services, tasks, processes, environments, and systems [239]. Although HFE is theoretically positioned as one of the most crucial components of the product development process, it is often not built in the early stages of prototyping, and many times incorporated at the later phases of the design process [79, 90, 140]. A last-minute effort of integrating HFE design principles or taking corrective measures on functional prototypes or products in use is regarded as reactive ergonomics approach [94, 118], which is usually associated with additional costs and time on the product development. The traditional reactive approach has several limitations when it comes to ensuring ergonomics requirements at the later stages [27, 91]. First of all, the primary design decisions and resource allocations are already made; thus, the application of HFE design principles becomes much constrained and restricted, which creates design solutions that are sub-optimal from an ergonomics standpoint [31]. These sub-optimal solutions present in the system, in the form of design deficiencies and poor human factors, lead to latent or catastrophic failures. Often the human operator gets blamed during an accident rather than the faulty design, which poorly considered human factors [176]. Secondly, even if the correct measures are applied, the modifications enforced on the system architecture cause additional ergonomics problems. On the other hand, the proactive ergonomics approach suggests that ergonomics must be built in the design process to reduce or prevent human-product interaction issues (e.g., the risk of injury, occupational injuries, and discomfort) preemptively by infusing HFE design principles during the early stages of product development [196]. Thus, proactive ergonomics provide a competitive edge to companies by creating products that potentially have better quality and enhanced usability [170].

Incorporation of HFE guidelines during product development requires the collection of human-product interactions data which is often not widely available [95]. The human-product interaction can be simulated by creating a physical prototype, computational prototype, or mixed prototype to collect data and incorporate HFE guidelines. Physical prototypes are advantageous in representing form and functionality; however, they are time-consuming and costly to build [40, 47]. Alternatively, computational prototypes cost low and take less time to build, but they lack representation of the physical interactions between humans and products, which limit the number of feedback [51, 142]. Another concern during prototyping is the amount of interactivity between the user and the product. Duffy (2007) mentioned that a physical prototype would be a better choice if a high-level interaction exists between the user and product. In contrast, when a low-level interaction exists, then the computational prototype is preferable [88]. What level of interactions to consider between the user and product lead designers into the dilemma about the type (physical or virtual), fidelity (low or high), and complexity of prototypes to build [88]. For example, Camburn et al. (2015) stated that there are no widely accepted guidelines on prototype building strategies to assist designers [54].

These limitations in the prototyping literature provide the primary motivation to undertake the current study. This research aims to create a Pre-Prototyping framework that aids designers to develop prototyping strategies to evaluate and design human-centered products and workplaces during the conceptual design process. The prototyping strategy includes both theoretical prototyping guidelines and practical fabrication guidelines. The proposed framework integrates prototyping theories, prototyping best practices, HFE principles, and computational HFE tools. It is found that there are not adequate prototyping theories and best practices related to the HFE and HCD based products. Additionally, there is a lack of HFE computational tools for designing and evaluating HCD based products. Hence, before the endeavor of developing the proposed Pre-Prototyping framework can be taken, the groundwork of developing the fundamental blocks of prototyping findings related to HCD and computational HFE tools needs to be developed. For this purpose, computational HFE tools such as Digital Human Modeling (DHM) are one of the fundamental elements of the proposed framework. Several studies are carried out to better understand the role of types of prototypes, levels of prototype fidelity, levels of human-product interactions, development of HFE computational tools based on Digital Human Modeling, and comparisons between different types of prototypes related to HCD based products. These studies led to the creation of various prototyping tools and prototyping findings used in conjunction with existing prototyping and HFE literature to develop the proposed framework.

1.3 Research Challenges

Designers often refer to anthropometry and HFE guidelines while designing human-centered products. Many human-centered design activities include assessing and evaluating products based on human performance. The feedback, required to measure human performance, can be captured from prototyping studies that represent the human-product interactions. While creating prototypes to collect feedback, the designers experience several challenges, which are as follows:

1) What prototyping guidelines should be followed to create prototypes?

2) What is the type of prototype: physical, computational, or mixed?

3) What should be the fidelity level of the prototype?

4) Does the human-product interaction level affect prototyping strategies? How can the human-product interaction level be addressed during prototyping?

5) Does the type of ergonomic assessment affect prototyping strategies?

6) What prototyping strategies should be adopted to capture human performance in the presence of various performance shaping factors (PSFs)?

7) How the human factor guidelines can be integrated earlier in the design phase and not just as a post-design ergonomic checklist?

8) What tools and technologies should be used to create the prototype?

9) What should be the prototyping strategy to address the psychological aspects of human performance ?

These research challenges are not comprehensively addressed in the literature. Also, there is either none or a limited set of prototyping guidelines that focuses explicitly on human-centered design challenges. For example, Camburn et al. (2015) stated that existing prototyping strategies are not widely accepted due to their limitations [54]. Menold et al. (2017) mentioned that existing prototyping frameworks are incomplete and have two critical gaps, not considering the human-centered design and practical evaluations [166]. In addition, Lauff et al. (2019) note that current prototyping strategies are difficult to implement into practice [144].

1.4 Research Questions, Objectives and Hypothesis

Due to the above theoretical and practical gaps found in the prototyping literature, particularly from the human-centered design perspective, the following research questions (RQ) and research objectives (RO) are formulated within the scope of prototyping strategies during the conceptual design of human-centered products. The research questions are divided into primary research questions and secondary research questions. The primary research questions deal with formulating the methodology to create the prototyping framework. The secondary research questions deal with prototyping tools and prototyping findings, which serve as building blocks for the underlying methodology that focuses on creating the conceptual prototyping framework.

1.4.1 The Primary Research Questions

Primary Research Objectives (PRO) and Primary Research Hypothesis (PRH) associated with Primary Research Questions (PRQ) are summarized below.

- **PRQ 1.** *What prototyping findings (best practices) and guidelines should be used for prototyping human-centered product?*
  - **PRO 1.** Extract prototyping findings from literature and form theoretical prototyping guidelines.
  - **PRH 1.** Designers who use the proposed theoretical prototyping guidelines will conceptualize better prototypes (related HCD based products)

than those who do not.

The outcome is a template or checklist that assists designers in selecting prototyping guidelines based on the ergonomic evaluation of the product and the availability of resources.

- **PRQ 2.** *What prototyping tools and technologies should be used to create prototypes for human-centered products?*
  - **PRO 2.** Extract practical tools and technologies from literature to build human-centered prototypes.
  - **PRH 2.** Designers who use the proposed prototyping toolbox will conceptualize better prototypes than those who do not.

The outcome is the prototyping toolbox. The prototyping toolbox is an inventory of prototyping tools and technologies that can be used to fabricate the required prototype.

- **PRQ 3.** What is the methodology to develop the Pre-Prototyping framework for HCD based products?
  - **PRO 3.** Create a framework that combines both the theoretical prototyping guidelines and practical prototyping tools to create a prototyping strategy.
  - **PRH 3**. Designers who use the proposed prototyping framework will conceptualize better prototypes than those designers who do not.

The outcome is a framework to create prototyping strategies.

1.4.2 The Secondary Research Questions

The primary research questions PRQ1 (prototyping findings) and PRQ2 (Prototyping tools) can not be addressed just by compiling the existing prototyping findings and prototyping tools. Hence, the secondary research questions are formulated to uncover new prototyping findings and tools about human-centered prototyping literature. Secondary Research Objectives (SRO) and Secondary Research Hypothesis (SRH) associated with Secondary Research Questions (SRQ) are summarized below.

- **SRQ 1.** What type of prototype (computational or mixed) should be used to capture the effect of Performance Shaping Factors (PSFs) (fire and smoke) on human performance (vision, posture)?
  - **SRO 1.** Understand how PSFs affect human performance and what prototyping strategies should be employed to capture the human performance.
  - **SRH 1.** Mixed prototyping approach is better in capturing human performance than that of computational prototypes when exploring the effects of PSFs (fire and smoke) on human performance (posture and vision).

The outcome is guidelines on how to incorporate PSFs in prototyping strategies to predict human performance.

- **SRQ 2.** How to use digital human modeling (DHM) research and digital prototyping tools to create a surrogate model and explore the design space for human-centered products?
  - **SRO 2.** Create a computational prototyping method that assists the designer in exploring the design space to integrate human factors in the conceptual design process.
  - **SRH 2.** The proposed computational prototype using CAD, DHM, and surrogate modeling explores a more extensive design space than the computational prototypes, which uses only CAD and DHM.

The outcome is using DHM and surrogate modeling to create a computational prototyping strategy.

- **SRQ 3.** How does the human-product interaction level, prototyping fidelity level, and type of ergonomics analysis affect the prototyping strategies of human-centered products?
  - **SRO 3.** Understand the levels of human-product interaction, level of fidelity, and ergonomics analysis plays a role in prototyping strategies.
  - **SRH 3.** Products that compromise higher human-product interaction should be prototyped using higher fidelity prototyping methods.

Table 1.1: Primary and Secondary Research Hypothesis

Hypothesis	**Chapter**
Secondary Research Question and Hypothesis (SRH) 1	2
Secondary Research Question and Hypothesis (SRH) 2	3
Secondary Research Question and Hypothesis (SRH) 3	4
Primary Research Question and Hypothesis (PRH)1	5 and 6
Primary Research Question and Hypothesis (PRH) 2	5 and 6
Primary Research Question and Hypothesis (PRH) 3	5 and 6

The outcome is to understand the relation among human-product interactions, the fidelity level of prototypes, and ergonomics analysis of the task and how they can be taken into account during developing prototyping strategies.

1.5 Road-Map

The primary and secondary research questions are answered in the subsequent chapters as shown in Table 1.1.

Figure 1.1 shows the roadmap for the work presented in this dissertation. Chapter 1 presents the overall goal, motivation, and research questions. Chapter 2 addresses SRQ 1 by developing prototyping findings related to PSFs. In Chapter 3 the SRQ 2 is answered by developing a design exploration method catered towards human-centered design by using DHM, Surrogate modeling, and Optimization tools. Finally, SRQ 3 is addressed in Chapter 4 by investing the relation among human-product interaction, prototyping fidelity, and type of ergonomics evaluation.

After SRQ 1, 2, and 3 are addressed, the PRQs are explored in Chapters 5 and

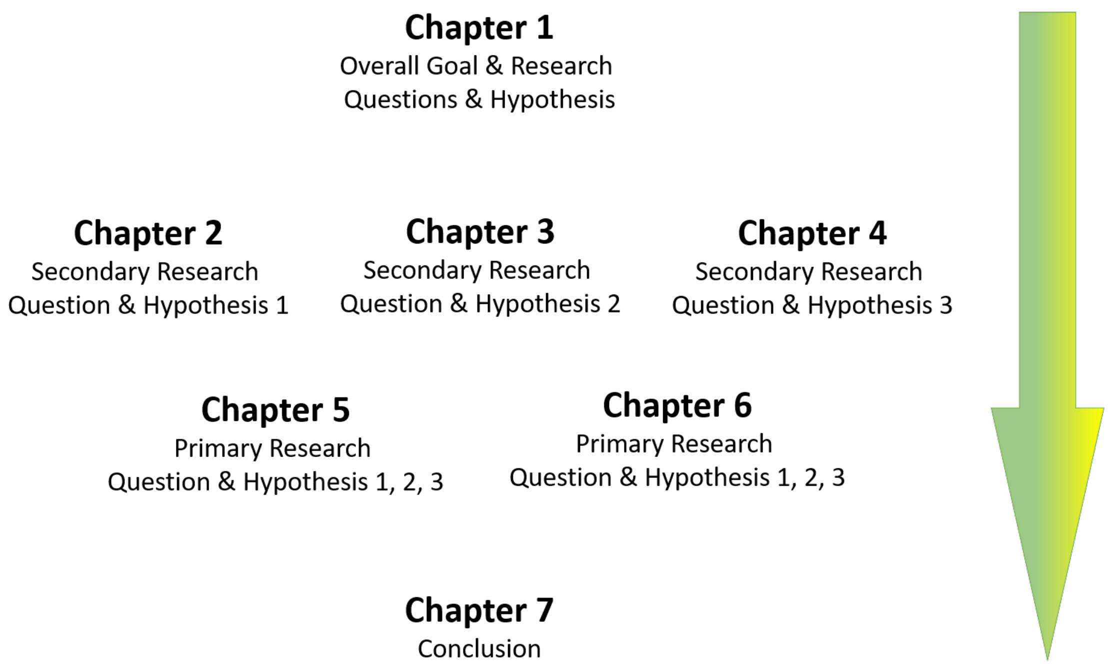

Figure 1.1: The Road-Map of the Dissertation

6, and the methodology to develop the prototyping framework is presented. The methodology contains prototyping guidelines and tools extracted from the state-of-the-art literature review about prototyping and HFE. It also includes findings developed based on the information presented in Chapters 2, 3, and 4. These guidelines and tools are analyzed and synthesized to form the proposed prototyping framework. Chapter 5 and 6 demonstrate the efficacy of the prototyping framework using multiple prototyping problems. A human subject experiment is carried out to confirm the validity of the prototyping framework, i.e., PRQ 1, 2, and 3. Finally, in Chapter 7, the conclusions, limitations, and future work is presented.

Chapter 2: A Framework to Assess Human Performance in Normal and Emergency Situations

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2.1 Abstract

Human error is one of the primary reason for accidents in complex industries like aviation, nuclear power plant management, and health care. Physical and cognitive workload, flawed information processing, and poor decision making are some of the reasons that make humans vulnerable to error and lead to failures and accidents. In many accidents and failures, oftentimes, vulnerabilities that are embedded in the system, in the form of design deficiencies and poor human factors, lead to latent or catastrophic failures, but the last link is a human operator who gets blamed or worse, injured. This paper introduces an early design human-performance assessment framework to identify what type of digital prototyping methodologies are appropriate to detect the deviation of the operator's performance due to an emergency condition. Fire in a civilian aircraft cockpit was introduced as a performance shaping factor. Ergonomics performance was evaluated using two prototyping strategies: (1) a computational prototyping framework, includes: digital human modeling, and computer-aided design; and, (2) a novel mixed prototyping framework, includes: motion capture, digital human modeling, virtual reality. Results showed that the mixed prototyping framework can simulate emergency scenarios with increased realism, also has the potential to incorporate subjective aspects of ergonomics outcomes, overcoming the underlying lack of design knowledge in conventional early design methodologies.

2.2 Introduction

Although safety-critical systems undergo rigorous testing and validation, costly and sometimes fatal accidents still occur. Classical studies in accident investigation and risk assessment have a long history of publication records addressing the root-causes of many accidents in complex systems such as health care, aviation, and power generation which occurred due to lack of creating a safe and accident-free 34 environment [180]. Human error has been identified as one of the primary causes for performance losses, accidents, and failures in complex systems [121, 158, 189]. For example, the National Academy of Medicine, formerly called the Institute of Medicine, reports that one medication error occurs per hospitalized patient per day [4]. Medical errors occurred in 2013 was ranked as the third leading cause of death in the US [158]. According to the report of the World Health Organization, the primary contributing factors for medical errors are human errors made by medical staff and workplace design or poor ergonomics [4]. Similarly, in the nuclear power sector, human error is identified as the primary reason for the majority of accidents. The Institute of Nuclear Power Operation (INPO) analyzed 180 significant event records that took place between 1983 to 1984. The analysis revealed that 92% of the time the root cause was human-related issues, where human performance-related problems and design deficiencies constitute the majority of the problems, 52%, and 33% respectively [190]. A similar trend in human error can also be found in the aviation sector. A number of studies have pointed out that between 60% to 80% of aviation accidents are found to be either directly or indirectly related to human error [116, 150, 207].

In order to reduce the human error and accidents associated with it, a comprehensive understanding of how human error occurs in human-product interactions must be identified. However, a universally accepted definition of human error does not exist yet [198]. One of the most widely accepted definition is given by Reason (1990) as *"a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency"* [191]. Thus, human error model must not just be classified as errors created by individuals in a personal level but also errors caused in the system level by various decision-makers, including policy makers, managers, and supervisors [192]. In addition, one needs to acknowledge that the human error stems from both the physiological and psychological limitations of humans [30]. Fatigue, workload, cognitive overload, flawed information process, and poor decision making are some of the reasons that make human vulnerable to error and lead to failures and accidents [117]. However, in many accidents and failures, oftentimes, vulnerabilities that are embedded in the system, in the form of design deficiencies and poor human factors, lead to latent or catastrophic failures, but the last link is a human operator who gets blamed or worse, injured [176].

In complex industries workers go through training, often loaded with procedural knowledge, and asked to follow checklists or guidelines so that tasks don't result in incidents [244]. However, it is reported that even when performing a routine task, such as normal start-up and shutdown procedure of a nuclear power plant, workers occasionally feel overwhelmed or burned-out [128]. In the aviation and health care sector, operators often deal with emergency procedures on a daily basis. These situations can range from monotonous and trivial emergency response activities to life-threatening and time-critical events [53]. For example, even though pilots and flight crew are meticulously trained to handle emergency situations, shortcomings that are evident in their responses decrease the safety [52]. A study showed that nineteen out of twenty-two times pilots are able to successfully cope-up with the textbook emergencies. However, only six out of eighty-five times they are able to successfully manage non-textbook situations [53]. This staggering observation shows that pilots can successfully apply their experiences gained from the flight simulator to avert familiar real emergency situations; but, when an unfamiliar emergency occurred, over 92% of the time they failed to successfully handle the situation.

Consider the example of a recent airplane crash happened on March 12, 2018, which is recognized to be one of the worst accident in the history of Nepal. The US-Bangla Airline Flight 211 took off from Dhaka, Bangladesh with four crew members and sixty-seven passengers, and crash-landed in Kathmandu-Tribhuvan Airport, Nepal [10,187]. The airplane was cleared to land on runway 02 but it was aborted by the pilot and requested to land from the opposite direction (runway 20). The controller denied the landing on runway 20 due to the traffic, and asked the pilot on which runway to land. The pilot requested landing on runway 20 and the controller cleared the airplane to land on runway 20. The pilot affirmed that runway is visible and proceeded with landing on runway 02. The controller also affirmed for landing on runway 02, though initially, pilot wanted to land on runway 20 and controller also cleared runway 20. The airplane touched down 1700 meters past the threshold on runway 20 and veered off to the left bank and ran through the inner perimeter fence of the airport. A fire erupted and all crew members along with forty-seven passenger died [187].

A complete official report on the cause of the accident has not been published yet. However, the preliminary report indicates a misunderstanding occurred between the pilot and the air traffic controller on which runway to land. It is also reported that there was a thunderstorm and cumulonimbus cloud 2500 feet above the airport and the pilot initially did not have the runway in sight [187]. The Kathmandu post of Nepal allegedly reported that the pilot was mentally stressed and reckless which caused the accident [2]. While the CEO of US-Bangla Airlines said to the Daily Star news of Bangladesh that the negligence of the controller to give specific instruction on which runway to land caused the crash [9]. Although the investigation is still going on, the preliminary report and some of the alleged claims address the role of human factors. This accident underlines the fact that instead of blaming individuals, efforts should be spent in trying to understand why a particular act or behavior seemed to be right to the individual at that time [75,76]. The same view is also shared by Reason (1990) in Human Error: *"Rather than being the main instigators of an accident, operators tend to be inheritors of system defects created by poor design, incorrect installation, faulty maintenance, and bad management decisions. Their part is usually that of adding the final garnish to a lethal brew whose ingredients have already been long in the cooking"* [191].

In this paper, we introduced an early design human-performance assessment framework to identify what type of prototyping methodology is appropriate to detect the operator performance during a routine and an emergency situation. We particularly focus on an incident or scenario that results in a deviation from the procedural tasks and demand increase in cognitive load. As mentioned earlier in the paper, workers and operators employed in complex and safety-critical jobs, where the probability of the injury or fatalities are high, are trained to follow specific formal procedures with the goal of mitigating unfavorable outcomes. However, previous research on non-textbook emergencies shows that failure to handle emergency procedures is high. In this study, digital prototyping methodologies are explored, and a novel prototyping methodology for capturing human performance in an emergency situation is introduced. Additionally, various performance shaping factors (PSFs), for example, poor visibility due to lack of lighting, are introduced to evaluate how the presence of PSFss affects the human performance and perceived cognitive load [135, 223]. Although there are various human factors assessments techniques are available in the form of guidelines, checklists, and surveys to measure human performance, the framework proposed in this study provides the opportunity to capture individual ergonomics differences early in design, computationally. Thus, it allows decisions regarding human factors to be incorporated during the conceptualization of products, processes or environments.

The remainder of the paper includes the literature review on the current state of the art of the computational human performance tools, types of prototypes, and simulations tools that are used to capture human interactions and performance with a product or within a workplace. A brief literature review of current practices in simulating emergencies is also provided. The proposed methodology to capture human performance is given in Section 2.3. Section 2.4 and Section 2.5 contain the specific case study we developed and results associated with the ergonomics outcomes. Finally, a discussion about the results and the conclusions about the study is given in Section 2.6 and Section 2.7 respectively.

2.3 Literature Review

The definitions and understanding of human performance and human-centered prototyping within the computational design are varied, depending on the domain of interest and the context of the design. For example, prototyping an user-interface may not require consideration of biomechanics and physical ergonomics, but the design of an exoskeleton or a wearable must address both the cognitive and physical capabilities of humans. The theory and methods used depends upon the context. While it is important to understand the terminology, it is equally important to acknowledge that providing exhausted coverage on human performance and human-centered prototyping is beyond the scope of this paper. Brief theoretical background information on the state-of-the-art design methodologies are provided within the context of computational ergonomics, specifically focusing on design and packaging of control rooms, workstations, and cockpits. This section is split into two main sub-sections with the goal of providing brief literature on human performance from the ergonomics perspective and a review of prototyping methods used in human-centered design studies.

2.3.1 Human Performance

Before presenting the literature on how to capture human performance, it is important to understand what human performance means, especially from the human factors engineering viewpoint. In general, performance is defined as outcomes, results, and accomplishments achieved by a person, group, or organization [197]. The study of human performance includes analyses of the processes that underlie the acquisition, maintenance, transfer, and execution of skilled behavior. It considers the fundamental human capabilities involved in understanding and acting on information arriving through senses [223]. Human performance can also be studied from the biomechanics and physiology perspective [62]. The factors that affect human performance, both carry cognition and physiology attributes, and they are known as performance shaping factors (PSFs) [135]. Some of the key human-performance shaping factors include:

1. Work environment such as noise level, illumination, temperature, and humidity.

2. Design of controls surfaces including the arrangement of controls, information, and control-display relationship.

3. Workstation layout and space, accessibility in normal working conditions, and escape routes during emergencies.

4. Industrial signing and labeling such as visibility and legibility of labels, location, and information transmission.

Items listed above include only a limited set of PSFs that can have significant effects on human performance both as individual entities or as a group. For example, in the design of a control room or a cockpit packaging study, having the right amount of illumination and the intuitive arrangement of controls as well as providing adequate working space and good accessibility are some of the entities that can positively affect the ergonomics outcomes. In contrast, absence or scarce representation of any PSFs would cause ergonomics issues regarding human-performance.

Another factor that influences human performance is the information processing capability of humans. The information processing is modeled as the three-stage process consisting of the perceptual stage, cognitive stage, and action stage [223]. The perceptual stage includes processes that operate from the stimulation of the sensory organs [241]. The cognitive stage includes the process such as information retrieval from memory, comparing displayed items, arithmetic operations, and decision making. Errors can occur in the cognitive stage due to a limitation in cognitive resources such as attention span, information retrieval, information analysis, and synthesis. Human factor specialists and designers should design the workplaces and tasks in such a way that the task should demand minimal cognitive workload from the user, and should not go beyond his/her cognitive capabilities. After the perceptual and cognitive stage, the user reacts or provides a response by performing an action [223]. To summarize, optimum human performance, both at the physical and cognitive level, lies at the heart of how the external factors used in the design of environments, products, or workplaces are blended, appropriately, with the consideration of the physical and cognitive capabilities and limitations of humans.

2.3.2 Prototyping in Human Centered Design

The terms "concept" and "draft" are used synonymously with prototyping to define an early version of a product that is released for the purpose of testing and analysis before finalizing the production requirements. The intention behind prototyping in human-centered design is to evaluate the usability and ergonomics of the overall concept to users before committing time and money into product development. Prototyping is a crucial and one of the most time and resource intensive phases of the product development process where engineers utilize concepts to agree on the form, fit, and functionality of a design before manufacturing and product decision are taken [182]. It's hard to come by an exhaustive list of prototyping methods since there is an endless number of techniques to build concepts ranging from cardboard modeling to additive manufacturing. Prototyping techniques within the engineering domain, perhaps, can be classified based on the variety, fidelity, and complexity to distinguish or compare different prototyping needs [133, 212, 219]. The first level of classification is regarding variety and describes whether the prototype is a physical or computation or a mixed model. The second level of classification focuses on the complexity of models or in other words whether the whole system (e.g., a complete car) or a sub-system (e.g., an engine block) is prototyped. The last level of classification is based on fidelity which focuses on how accurately the prototypes represent the final product [212]. This would include how the qualities of visualization (e.g., material textures) and functions (e.g., articulation and motions) generate a result very similar to a final or actual product. Within the human-centered design domain, along with modeling and drafting the mechanical aspects of a concept variant, designers require to evaluate the human performance and determine the level of human-product interactions within the prototyping stage [82].

There is a vast amount of literature on the skills and technologies used for prototyping, but the reasoning behind why, how, and when to employ prototyping is rarely asked in the design practice [225]. There is also a limited theoretical and practical frameworks available in computational human factors engineering domain to holistically assess mechanical and human aspects of prototyping early in the concept development. Creating the right type of prototype at the appropriate stage of the design process can help the designer to extract more information about human performance and improve the performance quickly and inexpensively [212, 224]. Starting by Section 2.2.2, we provide a summary of some of the best practices and the state-of-the-art prototyping approaches used for evaluating human performance.

2.3.2.1 High Fidelity versus Low Fidelity Prototyping

It is found in the literature that the early use of prototyping activities primarily focused on the physical aspects of conceptualization such as generating layouts, dimension, plans, and drafts via building physical models. With the advancements of computer technology, prototyping activities started to take a shift from physical construction to computational models [110]. One of the main concerns while developing a prototype is whether to build high or low fidelity prototype using either physical or computational models [230]. There are different views on what type of fidelity to choose during the prototyping process, but the final decision often depends upon how much resources can be allocated and how realistic the draft models needed to be both in terms of visualization and functions [110, 230]. For example, a low fidelity physical prototype made from cardboard and foam is used during the conceptualization of a domestic lighting controller to identify potential usability problems. This time and cost-effective approach help designers to identify a majority of the design problems and the revised design significantly reduced the number of the problems by 70% [110, 237]. However, a high fidelity digital prototype of the same lighting controller revealed 29 additional (or 100% more) problems when compared to the original low fidelity prototype. It is reported that the instant visual reaction and more realistic interaction helped to get more feedback from the user. Thus, revealing more problems but at the expense of greater time and cost [110]. Often, low fidelity prototypes that are rough and quick to make but represent the main attributes of a design are preferable to time-consuming high fidelity prototypes [46]. However, it is also found that low fidelity prototypes might not evaluate the physical attributes such as tactile, auditory, and visual feedback properly which are key factors in design studied that require humans (users, operators) in-the-loop [142].

2.3.2.2 Physical versus Computational Prototyping

Physical prototypes are generally created for the purpose of exploring design, communicating ideas, verifying the design criteria, and integrating specifications into the later design activities [225]. It is an effective way to experience the shape, composition, and functionality of a design. Traditionally, ergonomics analysis of a product is executed by creating a physical mock-up of a product (or a work environment) with specific attributes to be tested along with gathering human-subjects for data collection to find ergonomics discrepancies [28]. On the other side of the spectrum, it is found that physical prototyping is time-consuming to build, very costly, inflexible, and prone to error for data collection. For example, a typical ergonomics study in the car industry focusing on the three-dimensional physical prototyping of a seat-buck made from wood and metal can take up to six months to build. Furthermore, each round of design modification requires creating another new physical prototype, thus adding a lot of resources excess cost in terms of time and money to the development of the car design [40]. The disadvantages of high cost and time to build a physical prototype can be avoided by using computational models - often referred to as digital prototypes. Computational modeling in the context of prototyping is defined as a method to represent a series of static or dynamic graphical images via Computer Aided Design (CAD) models created in the form of mathematical representations that are stored in the computer memory. The CAD models represent the actual form and working functionalities of a concept product within a computer software that allows designers to generate multiphysics simulations or test the structural integrity of the concepts [252]. Computational prototyping has the potential to reduce the development cost by reducing the number of additional resources required for building costly physical prototypes. It is often regarded as a quick and cost-effective early design strategy to identify design flaws early in the design process. Thus, it brings the capabilities of minimizing time-to-market and increasing the quality of the final product [51]. However, computational or digital prototypes lack immersive experiences and user feedback (haptics) that contribute to sensory perception. Since there is no real users in-the-loop, a lack of interaction between the designer and user restrict the amount of information about the user feedback [142]. Thus, in the context of ergonomics, computational prototyping has a limited capacity to offer a comprehensive ergonomic evaluation.

2.3.2.3 Mixed Prototyping

Mixed prototyping is known as a virtualization technique that can blend both the capabilities of physical and computational prototyping by incorporating the advantageous features from each side and compensating the limitations by offering a more interactive experience. Bordegoni et. al. (2009) defines this technique as 'an integrated and co-located mix of physical and virtual components usually seen by means of a see-through head-mounted display (HMD)' [44]. Various studies showed that the key difference in mixed prototyping is not the use of advanced computer-based 3D modeling and projection techniques but the interactive and immersive technologies that enable human-product interaction which open novel venues to create prototyping strategies to add visual realism, auditory realism, tactile realism, functional realism [44, 175]. For example, a study focusing on the development of a novel multi-model interface called Immersive Modeling System (IMM) demonstrated that users wear HMDs to interact with a virtual object while grasping and manipulating the physical object with controllers. In this study, IMM is used to test the usability of a concept MP3 player and a game phone. Although users found that the interface provides more natural, intuitive, and comfortable interactions with the 3D product model within an immersive way, authors reported that within the IMMS interface, there can be a dissociation between tactile and auditory realism. In addition, limited or poor haptic feedback still causes some of the realism to be disregarded [36, 149]. Virtual prototyping offers a highly interactive experience in terms of visibility of the appliance or product but the accessibility and feedback are still limited. In a different study, Barbieri et. al. (2016), evaluated the effectiveness of the mixed prototyping approach within the context of usability of a washing machine interface. The physical prototype of the washing machine included features that allow users to configure the interface through changing knobs and buttons and allowing to represent different interface designs rapidly [47]. Although this approach is suitable for a system composed of conventional physical elements such as knobs and buttons, it is limited for digital applications where design interfaces are based on touch screens. Thus, it would become difficult if not impossible to represent various interfaces with only one physical prototype [36]. As a conclusion, within the human-centered design realm, the majority of the prototyping practices are heavily focusing on the usability testing and techniques used to build an interaction often vary drastically depending upon the design context (knobs versus touch-displays). Thus, even with the mixed prototyping approach what type of interaction method is used or how much of the concept design must be represented physically depend on designers' skill set and expertise, because most of the prototyping literature does not provide guidance, and even reasoning, regarding the fidelity, type, and at what design stage the mixed prototyping should be done.

In the next section, we will provide a summary of digital human modeling (DHM) as a computational prototyping technique from a human-centered design perspective, specifically focusing on human factors engineering and ergonomics of product development. DHM is often not covered within the human-centered prototyping publications but mostly treated as an ergonomics evaluation method within the embodiment phase of the product development. However, the real value of the DHM approach is in its capability to represent high-fidelity human attributes with visual realism and biomechanics early in the design phase.

2.3.2.4 Digital Human Modeling

Digital Human Modeling (DHM) refers to the development of advanced visualization, simulation, and ergonomics evaluation techniques and technology integration to create computational human models [186, 250]. DHM research brings visual and mathematical representation of humans with musculoskeletal and some cognitive characteristics within a computer or virtual environment [59, 214]. DHM is often used as a post-processing analysis method, based on a software application, to assess usability and ergonomics of 3D CAD concept products. The development of DHM research started around late 1960 and software tools are split into two major categories: physical and cognitive.

Physical DHM primarily focuses on the visualization and mathematical representation of musculature and skeleton of humans in a computer environment, including traditional domains of ergonomics, biomechanics, and physiology. The physical human models are often used evaluating the risk of injury based on the empirical motion and musculoskeletal data collected from human-subject studies. Body limbs are constructed as segments, and each segment is linked through ergonomic and anatomical mathematical models and constraints. Variation in populations and people are represented through anthropometric libraries which encompass anatomical and physiological data. Analysis methods developed in this area are based on biomechanical and statistical ergonomics models which evaluate applied forces on different body joints and segments. Software platforms often consist of 2D and 3D human-body representations, and able to generate ergonomics analysis based on previously established occupational safety, energy expenditure, posture, vision, and reach evaluations. These models are linked to ergonomics evaluation methods such as the National Institute for Occupational Safety and Health (NIOSH) lifting index and Rapid Upper Limb Assessment (RULA). Some of the physical performance assessment that can be accomplished within DHM software, including reach zone, obscuration percentage, joint comfort, and task time estimation. It is used in various sectors such as an automobile, aviation, assembly, medical, etc. [16, 68, 101, 143, 211]

The second type of DHM is focused on predicting the perceptual-cognitive aspects of human performance, mainly referred to as cognitive DHM or human performance process models, which focus on cognitive aspects of task execution. For example, models in this area attempt to predict the time required to execute a task or task performance under normal and high cognitive loads [57]. The goal of bringing cognitive capabilities to current DHM software is to increase the likelihood of identifying designs that increase mental workload, tiredness, monotony, and wear-out. Computational assessment tools that are currently under research target emergency management, game development, aviation, armed forces, and the manufacturing industries [214]. These tools are the computational versions of previously established human-system assessment methods, including Micro Saint, NASA TLX, CASHE Performance Visualization System [114, 146, 214]. Because of its abstract nature, variation in individuals and populations, and complexities and associated with human perception and cognition, the cognitive DHM is not as well-developed as the physical DHM [214]. This is the prominent reasons behind why the physical DMH models are more popular and adapted in the industry compared to cognitive models. Commercial DHM software lacks the automated cognitive evaluation tools because of the complexities associated with the cognitive aspects of the work. Also, each tool needs to be tailored to individuals since it is challenging to outline standardized procedures for the general population and task-specific scenarios. For example, psychophysical measures and their effects on individuals' mental load capacity or physiological stress differ a lot in population.

2.3.2.5 Prototyping Strategies for Evaluating Human-Product Interaction During Emergency Situations

An emergency is defined in Oxford dictionary as, *"a serious, unexpected, and often dangerous situation requiring immediate action"* [1]. Responding to an emergency is associated to increase in the workload, in many instances, not only just in the cognitive but also physical fatigue, and pushes humans to execute sub-optimal or even wrong actions [53, 116]. In aviation as well as many safety-critical complex industries, operators trained to rely on predefined emergency response plans in the form of procedures or checklist. For example, it is reported in the Aviation Safety Reporting System (ASRS) that over 86% of the time pilots successfully handle an emergency event in a text-book practice. However, during a non-textbook emergency event, only 7% of the time pilots are able to handle the situation successfully [53]. Therefore, it is important for operators to be trained in simulated conditions or scenarios that closely replicate real emergency situations. In addition, data gathered from these scenarios can inform engineers during the early design decision-making to have an optimized human-system integration.

In addition to aviation, other sectors such as healthcare, police department, fire department, terrorism, etc. also faces the challenges of emergency situation [132]. Professionals are trained in an educational setting to better prepare them on how to respond in an emergency situation. One effective approach to train professionals in emergency response is to use the live simulations [131, 132, 162]. It is the final step that the professionals go through to achieve the necessary competence to respond in emergency situations [132]. Jenvald et al. (2004) proposed an approach that has three factors such as modeling and simulations of the system, data collection, and visualization. The author mentioned that these factors are necessary to provide realism and unbiased observations. Live simulations are considered as 'gold-standard' for training professionals in emergency response, however, it is very costly, time-consuming and disruptive [67, 127]. Hence, other methods such as virtual reality are used and it is found to be accurate and an inexpensive alternative for emergency response training [67, 127]. Ingrassia et al (2015) performed a comparison study between virtual reality and live simulation for assessing medical students ability to carry out mass causality triage. It is reported that virtual reality simulation is equivalent to live simulation [127]. Another study found out that training medical students using electronic simulation tool increase their triage speed and score compared to the medical students who are not trained using electronic simulation tool [99]. Though there are different prototyping approaches such as virtual reality, live exercise, electronic simulation, etc., to evaluate emergency response, however, there are no widely available approach [98]. It is because live exercise can be accurate but time-consuming and expensive and on the other hand virtual reality can be inexpensive but lacks realism or may not be applicable in all emergency situations.

The lack of methods and guidelines on the type, fidelity, complexity of prototypes from a human-centered design perspective is especially problematic when prototyping an emergency. At the early stages of product conceptualization, engineers can leverage from a flexible prototyping method that has the capability of representing the product (e.g., cockpit controls) or works environment (e.g., cockpit) while keeping the users in-the-loop. This approach can help engineers to explore more on the human-performance - beyond the capabilities of what non-textbook emergency procedure can provide. An ideal prototyping environment for human-centered design must be replicating emergency situation in high fidelity and allow designers to extract data about how the human operator and design attributes work together. This is usually achieved by creating physical prototypes and by employing human subjects. However, employing human subject is dangerous in many emergency situations and creating a physical prototype is most of the time is costly and time-consuming, and sometimes infeasible. On the other hand, computational prototyping for emergency situation might not be applicable because of the limitations associated with human aspects of data collection. However, it is still critical to develop prototyping methodologies that are flexible enough to create a variety of non-textbook emergency situations. It is equally important to provide prototyping guidelines that summarize what method is best to use based on the variety, fidelity, and complexity of the human-system interaction. Other important properties are that the prototyping method must not compromise human safety and it could extract reliable information about human-performance within a short amount of time, cost-effectively.

2.4 Methodology

A large growing body of literature investigated in Section 2 shows that most of the simulations or prototyping strategies to evaluate human performance is based on the usability testing approach, which often involves physical prototyping and human-subject data collection. Most of the studies in the field of human-performance analysis within human factors engineering have predominately focused on the techniques used in the usability assessment, including experimental design, testing protocols, data analysis, and validation. To date, there hasn't been a comprehensive guideline on the type, variety, and complexity of what type of prototypes to be built based on the human-centered design needs. High cost and excessive time spent in building full-scale physical prototypes hinder the use of physical prototyping as an early design solution; thus, resulting in sub-optimal products or workplaces. On the other hand, virtual or computational prototyping to evaluate human performance is not as resource intensive as the physical prototyping but it lacks fidelity. A prototyping strategy for evaluating human-product interaction for emergencies is necessary to correctly assess human performance. Although physical prototypes are resource intensive, they can produce high fidelity human performance assessments. However, emergency situations often involve hazardous activities and environments, which increases the risk of injury or threaten the safety of human subjects. On the other hand, the digital or computational prototypes does not suffer from the safety concerns since no human subject is employed; however, the issue of low fidelity (because of no feedback from the human subjects) is a significant hurdle. There is a need for a virtual or computational prototyping methodology that is capable of predicting human performance in an emergency situation with high fidelity [214]. One solution, proposed in this paper is a mixed prototyping approach which simulates an emergency condition while keeping the human-subject in-the-loop. However, since mixed prototyping takes elements from both the physical and virtual prototypes, it comes with the advantages and disadvantages that are inherent to physical and virtual prototyping. Also, there is a pressing need for exploring mixed prototyping capabilities in terms of human-performance assessment in early design of products. There is a little or no comprehensive guidelines provided, such as (1) what portion of the product or workplace needs to be physically made; (2) what portion should be computationally represented; and, (3) what are the resulting fidelity level will be. So the designers are in a dilemma on what type of prototypes or simulations should be used to assess human performance, especially in product development scenario where emergency situations need to be modeled or simulated. Figure 2.1 shows a visual guideline on what type of prototypes to be built to assess human performance in for an emergency modeling early in the design process.

In Figure 2.1, prototypes are classified based on the variety (computational,

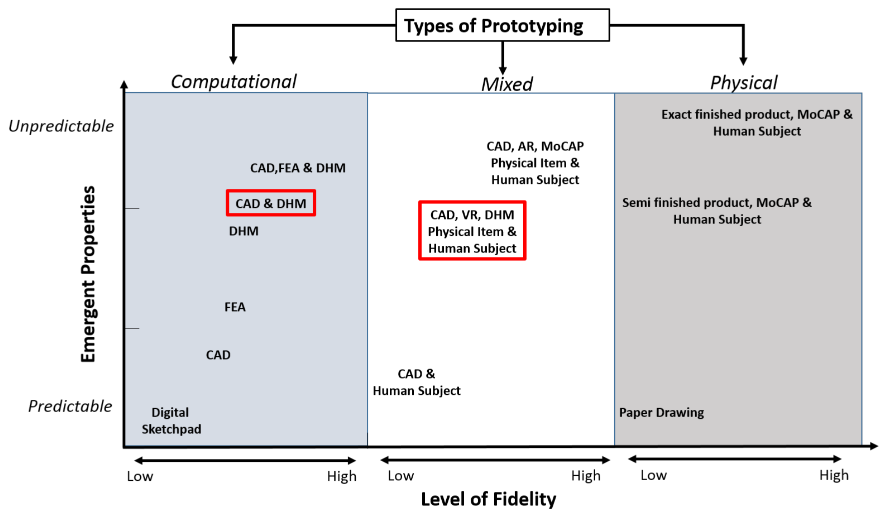

Figure 2.1: Types of Prototypes for assessing human performance in Emergency Situation adapted from [25]

physical, and mixed) and level of fidelity (high and low) in the horizontal axis. The prototypes are further classified according to the emergent properties of the product or workplace in which the human users or operator is working as shown in vertical axis. The emergent properties of a product can be predictable if the functionalities or behaviors of the product is known - through prior experience or intuition. For example, one can predict the outcome of what could happen when pressing the on/off switch or using the setting to increase or reduce the rotation speed on a home blender. In contrast to a simple home blender, products with novel or not previously known complex set of functionalities (e.g., an airplane cockpit or a control room of a nuclear power plant) can reveal an endless amount of outcomes which are not available to operators' intuition. Additionally, the behavior of complex products can be tightly coupled to the external factor such as the ambient temperature, illumination level, percent visibility, and air flow direction. These factors may have additional influence on the system level which makes it hard to predict the final behavior.

Throughout the rest of this paper, a case study taken from civilian aviation was modeled as an emergency testbed scenario. The case study was explicitly selected to explore what type of prototyping methodologies can assist designers to evaluate the human performance within nominal and emergency operating conditions. More details on the case study and the prototyping methodologies are provided in Section 4. Human performance assessments in this research were evaluated using two types of prototyping methods:

1. A computational prototyping approach created by integrating CAD and DHM.

2. A mixed-prototyping approach created by integrating human subjects, CAD, a marker-less motion tracking device and a VR simulation via HMD.

Prototyping methods used in this study are represented in Fig. 2.1 with square boxes in red color. The primary goal of our research is to develop prototyping methodologies for early design evaluation of human-performance, specifically focusing on the conceptualization phase of product development. Thus, a physical prototyping approach, including the construction of an actual physical workplace with real smoke and fire experiments were out of the scope. Instead, our goal was to provide a schema on prototyping strategies that are explicitly focusing on the conceptualization of early design alternatives that require "quick-and-dirty" decision making, yet, still providing good fidelity. Thus, we focused on computational and mixed-prototyping strategies as areas to explore.

2.5 Prototyping Case Study - Modeling Fire Emergency in A Civilian Cockpit

The emergency situation studied in this paper was taken from an actual emergency case study where smoke and fire in a cockpit develops due to a faulty, loose heater screw in a few numbers of Boeing 7X7 airplanes [3, 5]. The faulty heater causes fire to erupt in the cockpit, fills the cockpit with smoke, shatters inner ply of the windscreen. For example, a flight from Puerto Rico to Philadelphia in 2008 was diverted to Palm Beach, Florida to make an emergency landing. During this emergency situation, pilots initially put on the oxygen mask and checked the instrument panel, switched-off the auxiliary power on overhead panel, then used the fire extinguisher to kill the fire and smoke [3]. In this paper, the emergency situation was created within digital modeling by adding artificial smoke and fire to the prototyping model as performance shaping factors (PSFs). The emergency conditions were simulated using two types of prototyping methodologies to understand what type of prototype is suitable for replicating human performance during an emergency situation. We used computational and mixed-prototyping methodologies that take into human attributes via DHM to assess performance parameters such as joint angles and percent vision obscuration. A 3D CAD replica of a Boeing 767 cockpit, shown in Figure 2.2 (a), used in both prototyping methodologies.

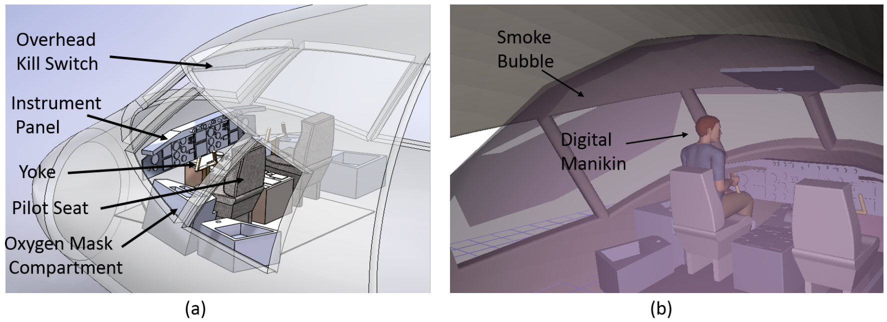

Figure 2.2: (a) Partial CAD model of Boeing 767 and (b) Computational Prototyping using CAD and Siemens Jack

2.5.1 Computational Prototyping Study

As mentioned earlier that pilots are trained to go through procedures or checklist to address emergencies. In our case study, the sequence that pilots followed started with putting the oxygen masks on, followed by checking the instrument panel and reaching to the overhead panel to push the kill switch. Thus, the detailed environment model that includes the necessary components of the CAD model which makes up the cockpit model such as the fuselage, oxygen mask compartment, instrument panel, overhead board, pilot seat, and yoke are shown in Figure 2.2 (a). The CAD model was then imported into Siemens' human modeling and simulation platform called Siemens Jack [6]. Within the Jack software, a digital manikin representing the pilot was created through the Anthropometric Survey of US Army Personnel (ANSUR) database and inserted in the cockpit as can be seen in Figure 2.2(b). The digital manikin was custom scaled to fit the human subjects used in the mixed prototyping study, which ensured that the same anthropometry was used throughout the prototyping studies. In the computational prototype, CAD smoke model was built as a translucent sphere/bubble which roughly represents the typical area smoke could occupy in the cockpit. Figure 2.2(b) shows the computational prototyping setup, including cockpit model, manikin, and smoke bubble. Throughout the computational prototyping study, two human-performance measures were used:

1. Joint angles (head and upper arm flexion) during the reach posture, specifically when reaching the oxygen mask, instrument panel, and kill switch.

2. Vision performance evaluated based on percent obscuration zones.

2.5.2 Mixed Prototyping Study

The mixed prototyping setup was created by utilizing the same CAD model from the computational prototyping study as shown in Figure 2.2 (a). Different than the computational prototyping approach, the CAD model was imported into a VR platform named SimLab VR Viewer [7]. In this study, an actual human-subject was coupled with the Jack interface through a markerless motion capture system. A human-subject with 167 cm in height and 72 Kg in weight was created in Jack. The objective of this setup was to enable an actual human-subject to drive the Jack manikin while navigating through the CAD model and interacting with the cockpit elements via HTC VIVE virtual reality system [174]. Throughout this study, the human-subject sat on a physical chair whose position was calibrated and corresponded to the virtual pilot seat in the VR simulation. Meanwhile, the human-subject carried VR wands on both hands that were aligned to the position

Figure 2.3: Mixed Prototyping using CAD, SimLab, VR and Human Subject

of the virtual yoke. This setup mimicked an actual cockpit usage scenario where the human-subject sat on the pilot seat and used the yoke to interact with the cockpit elements. Similar to the computational prototyping study, the emergency condition was modeled by using artificial smoke. However, the smoke was a dynamic graphics simulation which was moving around as opposed to the stationary CAD smoke sphere/bubble used in the computational prototype. The difference was primarily due to the fact that the VR platform allows the dynamic representation of modeling elements wherein only a generating static CAD modeling was possible in Jack to represent the smoke effect. In addition to the smoke effect, a fire effect was also added by simulating a virtual fire within in the cockpit as shown in Figure 2.3. The dynamic effects of smoke and fire built in the mixed prototyping study via VR integration closely resembled the real smoke and fire in a cockpit, thus increasing the fidelity as well as the interactivity when compared to the computational prototyping methodology.

2.5.3 Experimental Setup

The effect of two different prototyping strategies (computational and mixed prototyping) and their capability on capturing human-performance measures in normal/routine and emergency work conditions were compared. The CAD model representing a civilian airplane cockpit in Figure 2.2(a) was used both at the routine and emergency condition. For injecting emergency into the work environment, artificial smoke and fire were added to the prototyping setups as performance shaping factors (PSFs). Only an artificial static smoke was used in computational prototyping, whereas a dynamic smoke, as well as a fire simulation, was added to the mixed prototyping setup. In both conditions, a specific sequence of reach tasks that pilots had to go through in the case of smoke or fire emergency in a cockpit was followed, including reaching oxygen mask, reaching instrument panel, and reaching kill switch in the overhead panel. In the computational prototyping study, the reach task sequence was executed by manipulating the posture of the DHM manikin-based on the inverse kinematics method each step at a time. In contrast, during the mixed prototyping study, a human-subject coupled with the DHM manikin went through the reach sequence in an immersive way via VR headset. A markerless motion capture device built via the Kinect sensing technology was used to drive human manikin in DHM through capturing changes on the upper body joint angles. There wasn't any need for a motion capture setup during the computational prototyping strategy because the DHM manikin motion is based on the inverse kinematics controls in Jack software.

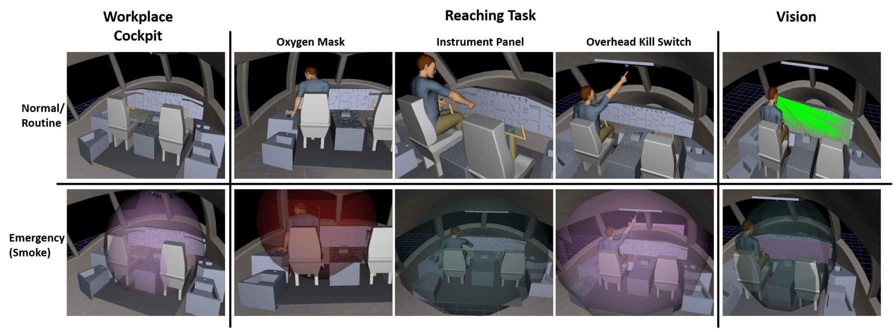

Figure 2.4: Assessing Human Performance in Normal and Emergency Situation using Computational Prototype

Throughout this study, two ergonomics analyses (joint angles and vision) were performed to measure human-performance. In addition, a NASA-TLX cognitive workload assessment was performed during the mixed prototyping study to capture perceived workload of the human subject. The joint angle measurements were calculated based on the change in posture at each reach task. The vision performance parameters of pilots were evaluated through obscuration zone analysis technique, which measures the percent area of the binocular vision blocked by the presence of the cockpit elements or by PSFs - the artificial smoke and fire. The percentage area was measured by computing how much of the graphic rays (highlighted in yellow in Figure 2.4), which are protruding roughly at the eye-center, reaches to a target plane located at a specific area of interest.

Table 2.1: Human Performance During Routine and Emergency Procedure using Computational Prototype

Reaching Task	**Angles**	**Routine°**	**Emergency° (Smoke)**
Oxygen Mask	Head	28.6	28.6
	Upper Arm (Left/Right)	3.5	3.5
Instrument Panel	Head	16.2	16.2
	Upper Arm (Left/Right)	53.4	53.4
Kill Switch	Head	-5.8	-5.8
	Upper Arm (Left/Right)	126.5	126.5
Vision	Coverage Percentage	99.55	99.55

Table 2.2: Human Performance During Routine and Emergency Procedure using Mixed Prototype

Reaching Task	**Angles**	**Routine°**	**Emergency° (Smoke)**	**Emergency° (Smoke and Fire)**
Oxygen Mask	Head	0.867	3.500	5.200
	Upper Arm (Left/Right)	5.467	0.600	2.100
Instrument Panel	Head	12.667	19.667	6.300
	Upper Arm (Left/Right)	33.500	22.433	18.433
Kill Switch	Head	-0.133	0.100	1.900
	Upper Arm (Left/Right)	35.700	17.933	15.833

Table 2.3: ICC and Descriptive Statistics for Various PSFs using Mixed Prototype

	Intra-Class Correlation (ICC)	**95 % Confidence Interval(CI) Lower - Upper**		**Sig.**	**Mean**	**Variance**
Routine - Emergency (Smoke)	0.867	0.215	0.981	0.022	12.69	183.18
Emergency (Smoke) - Emergency (Smoke and Fire)	0.877	0.263	0.982	0.019	9.5	78.95
Routine - Emergency (Smoke and Fire)	0.791	-0.098	0.969	0.038	11.48	154.7

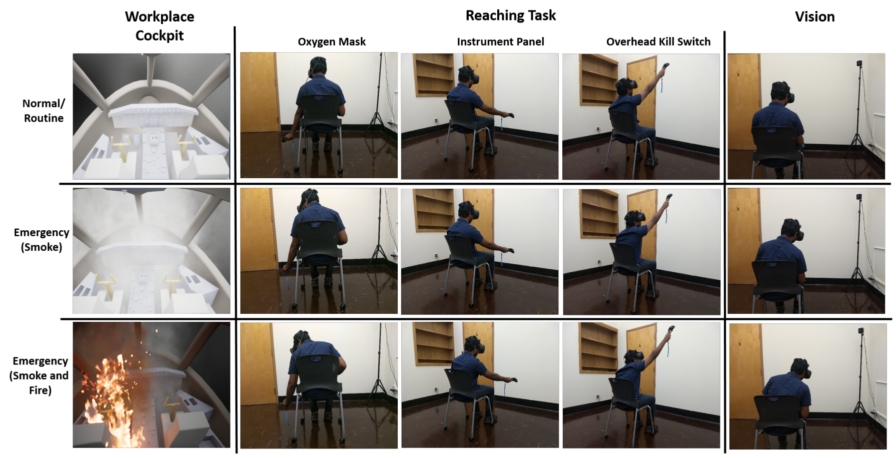

Figure 2.5: Assessing Human Performance in Normal and Emergency Situation using Mixed Prototype

2.6 Results

2.6.1 Observations and Outcomes - Computational Prototyping Study

Figure 2.4 summarizes the computational prototyping setup including simulation screen captures that present reach tasks within normal and emergency conditions. Each column represents specific reaching tasks (reaching oxygen mask, instrument panel, and overhead kill switch) that the pilot (DHM manikin) executed during the reach simulations. One can see that in the normal/routine setup the DHM manikin went through the procedures without the presence of smoke. However, in the emergency scenario, DHM manikin performed the same sequence of tasks in the emergency situation where the effect of smoke was injected into the simulation environment via a transparent sphere/bubble. The last column on the right-hand side of Figure 2.4 shows how the vision analysis (obscuration zone via percent visibility) was performed within DHM environment with and without the presence of the artificial smoke sphere/bubble. Table 3.1 provides a summary of joint angles and a comparison of the data between normal and emergency conditions using only computational prototyping method.

2.6.2 Observations and Outcomes - Mixed Prototyping Study

In the mixed prototyping study, the exact sequence of tasks carried from the computational prototyping study was repeated by the human subject who went through the tasks via VR setup and the change in the upper limb posture was recorded by the motion tracking device. The motion data, in real-time, was linked to the DHM analysis toolkit to generate joint angle outcomes. Figure 2.5 summarizes the mixed prototyping setup including simulation screen captures that illustrate reach tasks performed in normal/routine conditions and emergency conditions. Different than the computation prototyping study, an additional level of emergency PSFs (fire) was introduced on top of the emergency condition with artificial smoke. Each subject trial was randomized and the reaching tasks were repeated three times. The summary of the average posture angles is shown in Table 2.2. The Intra Class Correlation between joint angles in three different reaching tasks and descriptive statistics are also provided in Table 2.3. The NASA-TLX workload assessment for the routine, emergency (smoke), and emergency (smoke and fire) conditions using mixed prototype are presented in Table 2.4.

The objective data provided in Table 3.1 and 2.2 is analyzed using Intra-Class

Table 2.4: Perceived Workload Assessed Using NASA-TLX

	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Overall Rating
Routine	65	40	65	25	70	35	53.33
Emergency (Smoke)	75	30	75	45	75	70	68.67
Emergency (Smoke and Fire)	95	30	95	60	75	70	82.67

Correlation (ICC) test as shown in Table2.3. A value of 1 represents a perfect match, and a value of 0 represents no match. In similar ergonomics studies, a correlation range and guidelines between 0.8 to 1.0 was recommended as a good test-retest reliability range [81, 97, 220].

2.7 Discussions

Human performance measures estimated in terms of reach angles differ between computational and mixed prototyping studies. Joint angles measured at each reach task in the computational prototyping study yielded identical values no matter how many times each task was replicated. The inverse kinematic manipulation option within the DHM software generates exactly the same posture each time the manikin was manipulated to reach the targets (oxygen mask, instrument panel, overhead kill switch). In our case, the end-effector, the tip of the right-hand index finger (distal phalanx), was manipulated manually via kinematic controllers in the Jack interface to reach control buttons or knobs at known reach targets. Since the starting posture of the manikin is fixed (standard airplane operating posture) and the end-point of the structure is known (reach the target - oxygen mask); thus, the range of possible trajectories or solutions converge into a single solution set - identical joint angles. One can see from Figure 2.4 and Table 3.1 that the posture angles and vision are exactly the same and they do not differ between the normal and emergency conditions. In contrast, data collected during mixed prototyping study provided more enriched data in terms of a range of joint angle values. This is because a human-subject coupled with the motion capture device was independently driving whole-body posture of the DHM manikin, not just manipulating the end-effector. Thus, the whole-body kinematics analysis generated a range of possible solutions since each reach motion attempted by the human-subject results in a novel trajectory. A similar observation was made in the context of obscuration zone analysis. In computational prototyping study, percent obscuration analysis revealed identical results since the manikin was surrounded with stationary smoke which was dispersed homogeneously within the cockpit. Thus, the effect of the static smoke on binocular obscuration did not vary with a change in posture. In the mixed prototyping study, the dynamic smoke simulation cause areas of light and heavy smoke throughout the cockpit, and in times it made the human-subject change his posture to glance at the instrument panel. Also, injecting an artificial fire into VR simulation as an additional performance shaping factor on top of the smoke in mixed prototyping study resulted in different joint angles. Figure 2.5 shows as the situation change from normal to emergency with “smoke” to “smoke and fire”, the posture of the human subject changes slightly. A slight increase in the head flexion angles was observed while reaching oxygen mask and kill switch. In contrast, the human-subject perceived a different trajectory for reaching the instrument panel, and a significant decrease in the head flexion angles was noticed. One can see the upper arm flexion angle only increased in while the subject was reaching to the oxygen mask. A slight decrease in the upper arm flexion angle can be seen when reaching the oxygen mask and kill switch tasks Table 2.2.

In this study, Intra-Class Correlation (ICC) scores ranged between 0.79 to 0.867 as shown in Table2.3, which demonstrates a good test-retest reliability of the mixed prototyping methodology. In addition to the statistical analysis of the objective data, the subject's perceived mental workload assessment, based on the NASA-TLX analysis was summarized in 2.4. The cognitive assessment via NASA-TLX provided an additional layer of information about the subject's understanding of the environment or tasks since DHM simulations in computational prototyping method lack the subjective input and do not allow replication. As noted earlier, due to the limitations of the inverse kinematic manipulation approach, there is no room of generating different trajectories or reach patterns; thus, making DHM incapable to incorporate subjective aspects, as well as cognitive aspects, of human performance early in design. As can be seen in Table 2.4 that the overall mental workload rating is highest in the emergency condition where both fire and smoke were present as PSFs, the emergency condition only including the smoke perceived second. Routine condition revealed the lowest overall rating. The mental demand, temporal demand, and frustration ratings were also highest in emergency condition with "smoke" and "fire" followed by the emergency condition of only "smoke". Similarly, performance success received the lowest rating in routine condition when compared to emergency conditions.

2.8 Conclusion and Future Work

The findings of the study indicate that a mixed prototyping approach is more suitable in capturing human performance in an emergency situation in comparison to a computational prototype. Performance shaping factors such as smoke and fire create a sense of emergency which drives the human subject to act differently by causing a change in human posture. The change in human posture was measured by coupling a motion capture system with DHM software, and the perceived workload was assessed using NASA TLX.

This research is proposed as a pilot study of a mixed prototyping framework with the goal of assessing whether coupling DHM, motion capture, and VR technologies can capture human-performance within emergency conditions early in product conceptualization. Although only one human subject was used in this pilot study, the novel prototyping setup and the outcomes of this study provide important insight into human performance assessments strategies for concept product development and computational ergonomics. In addition, the Kinect-based motion capture system that was coupled with the DHM does not provide a very high fidelity data capture solution when compared to marker-based optical multi-camera tracking systems. Also, we only focused on the static aspects of the tasks and did not analyze the dynamics aspects of reach. A more comprehensive posture analysis with dynamic aspects would reveal further on how the emergency conditions affect the posture human-performance. However, an exhaustive empirical ergonomics or cognitive study goes beyond the scope of this paper. The goal of in this paper is to inform designers about an alternative early design method that uses state-of-the-art computation method for human-performance assessments. In contrast to embodiment or production planning phases of the design process where fine-tuned analyses and experiments are sought, most of the early design efforts focus on ideation, concept development, and filtering infeasible ideas. Thus, a developing "quick-and-dirty" human-product interaction framework is more prominent at early design process than comprehensive design evaluation methodologies.

The future study of this paper is to perform a comprehensive study by employing additional human subjects, physical prototypes and higher fidelity motion capture which can be used to validate the study. The physiological validation, i.e. reaching posture validation can be achieved by comparing the reaching posture obtained using mixed prototype with the reaching posture obtained by higher fidelity physical prototype for a group of human subjects. The reaching postures obtained from the two types of prototypes can be statistically analyzed to determine whether there is a significant difference present or not. If the reaching postures are not significantly different then the physiological results of the mixed prototype are validated. Additionally, the psychological validation can be done subjectively and objectively by comparing the workloads from the mixed prototype and higher fidelity physical prototype. NASA TLX can be used to subjectively assess the perceived workload of the human subjects who are exposed to either mixed prototyping or physical prototyping. The workload can be measured objectively by observing the ocular, respiratory response, brain and cardiac activity [122]. If the psychological result obtained from the two prototypes are not statistically different then the mixed prototype is validated. Furthermore, since this study indicates what type of prototype can capture human performance, authors intended to develop a future study on how mixed prototypes of different fidelity can affect human performance.

Chapter 3: Integrating Human Factors Early in the Design Process using Digital Human Modeling and Surrogate Modeling

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3.1 Abstract

Embedding ergonomics in the design process is often delayed as it requires building physical prototypes and human subject data collection. This causes retrofitting or expensive late design changes which increase overall cost and time-to-market. This paper presents a computational design methodology that employs Digital Human Modeling (DHM) research and the surrogate modeling technique to integrate ergonomics early in design. The goal of this methodology is to provide a proactive ergonomics assessment toolset that allows designers to identify the effects of design variables on human performance, computationally. In this research, a design space exploration study was conducted to evaluate the ergonomics of a concept aircraft cockpit model built based on a set of flight deck layout variables. Variability in the pilot's anthropometry was added through accommodating the extremities in population-based on computational human manikins. A genetic algorithm with the surrogate model was used to search the concept variants that meet ergonomics objectives. The results show that the proposed proactive ergonomics approach allows designers to explore the design space and evaluate trade-offs between the competing design objectives early in design. Our computational ergonomics approach, based on the cockpit packaging study, demonstrates the advantages of the DHM based surrogate modeling during product conceptualization.

Keywords: Human Factors Engineering, Design, Digital Human Modeling, Surrogate Modeling, Design Space Exploration

3.2 Introduction

Injecting human factors engineering (HFE) and ergonomics design principles into the product development process improves the overall quality and reduces production costs [58, 78, 89]. A study conducted by interviewing five Swedish companies by [94] about the obstacles and needs of proactive ergonomics measures early in product development showed that 58 out of 64 design engineers agreed that poor ergonomics practice creates inferior products. However, one of the main roadblocks to integrating human factors early in the design process is the need to create a physical prototype to collect human subject data [95]. For example, prototyping a wooden or metal seating buck model can take up to six months, whereas a computational prototype can be built in a much shorter time [40]. In addition to the time and finances related limitations, collecting human subject data via physical prototyping becomes dangerous (e.g., facilities with hazardous material handling), infeasible (e.g., outer space habitation design), or not readily available (e.g., submarine design) [58].

The advancement in computational power and graphical visualization has circumvented some of the limitations of high-fidelity physical prototypes and human subject data collection by introducing computational prototypes and digital manikins [58,89,214,250]. For example, Digital Human Modeling (DHM) research brings computational design support tools for engineers to perform ergonomics assessments early in design [16, 79, 214]. There are many DHM software such as Siemens Jack [188], RAMSIS [50], 3DSSP [96], Santos Pro [14], HADRIAN [159] that are commercially available. Likewise, many industries such as aviation [168], automobile [240], assembly, and manufacturing [251], consumer goods [69], healthcare [49] have embraced DHM and uses computational manikins in their product design processes.

Literature shows research related to DHM can be divided into two parts. The first part is about developing the scientific understanding (anthropometry, posture, biomechanics) and algorithms that can be used to create, and/ or, improve the functional capability of DHM tools [14, 48, 193, 247]. The second part focuses on the application of DHM in the product design process. This paper concentrates on the second part. Literature related to the application of DHM heavily ponders on the ergonomic evaluation of products. Numerous prior work showed that DHM is used solely as an ergonomic assessment or a check-gate tool. Typical examples include furniture design [209], material handling tasks in vehicle assemblies [109], snow shovels [242], pedal thrasher [138], and automotive manufacturing [173]. Once an ergonomic discrepancy is discovered in these cases, engineers suggested design changes based on their expertise or intuition. This approach results in a poor evaluation of the concept alternatives, and engineers often end up under-exploring the design space and creating sub-optimal products. However, DHM provides a broader set of design support tools, which enable designers to use the computational manikin approach within a more holistic perspective. In this paper, we propose that DHM should not be used solely as an ergonomic assessment tool but as a part of the entire design process. Our DHM-based design approach promotes that the ergonomic assessment data can be used to identify critical design variables, create meta-models, and design objectives that can be used for systematic design exploration.

This paper's motivation is to demonstrate an alternative computational method that helps designers systematically apply HFE design principles during the early stages of the design process. In this research, we propose a computational design methodology based on Digital Human Modeling (DHM) research [58, 89, 170] and surrogate modeling technique to evaluate concept designs for ergonomics research. A surrogate model based on DHM simulations is built to generate a design space, including design variables and human factors requirements for a cockpit packaging design study. The meta-model is explored to identify design alternatives where the human performance measures are optimal. Thus, this research aims to explore a computational human factors design framework where concept designs are systematically screened earlier, and ergonomically weak or infeasible design points are pruned before committing to physical prototyping.

The summary of the design methodology, the computational validation study, and a cockpit packaging design study taken from the aviation domain were delved into providing a conceptual template about how DHM can successfully support early design HFE assessment efforts. The cockpit packaging study demonstrates how it supports designers to make better decisions regarding ergonomics early in the conceptualization stage — before any costly physical prototypes are built, or design commitments are made.

3.3 Literature Review

3.3.1 Digital Human Modeling (DHM)

DHM is defined as the research domain that is dealing with the development of advanced visualization, simulation, and ergonomics evaluation techniques and technology integration to create computational human models [186, 250]. DHM offers designers the capability to visualize and evaluate some of the ergonomics performances early in the design with the integration of 3D computer-aided design (CAD) models [58, 214]. This proactive approach has the advantage of reducing the need for full-scale physical prototyping and eliminating some of the extensive human-subject data collections. DHM also enables designers of various disciplines to incorporate HFE principles early in the design to evaluate the safety and comfort of concept designs. Commercially available DHM software has data import features where designers can bring CAD models and create manikins with different anthropometric characteristics [58, 170]. By bringing the CAD models of a prospective workspace with a computer-rendered avatar, designers can assess ergonomics issues such as fit, reach, and vision-obstruction zones [61]. Though DHM offers many capabilities to designers it also has some limitations. One of the limitations is if the simulations are not done properly and the results are not analyzed by designers having some knowledge of the human factors, then the results might be misleading. Some other areas where DHM can be improved is fidelity, simulation of a complex task, consideration of aging and disabled population, comfort/discomfort measurement, seamless integration of CAD and DHM, cognitive analysis, etc. [58, 60, 136, 214].

Although DHM research brings advanced visualization and simulation techniques to the human factors domain, it is mostly used only as an ergonomic assessment tool (i.e., whether a product or workspace meets the ergonomics requirements) — rather than being employed as an actual design methodology [77, 82, 126, 211]. This limited approach puts a constraint on ergonomists' early design stage capabilities and restricts the goal of designing with computational human models.

In this study, we employed DHM as the actual ergonomics design interface to bridge the digital CAD models and performance measures without the need for constructing physical prototypes. Thus, the early design approach promoted in this study demonstrates how DHM tools can be applied during the concept generation process to inject HFE design principles into the products.

3.3.2 Human Factors in Early Design Process

There have been numerous human-centric design methodologies introduced, such as Human-Centered Design (HCD) [108] and Design for Human Factors (DfHF) [226], to integrate HFE techniques early in the design. However, none of these methodologies focus on injecting HFE as early as the concept design review stage. They often target the embodiment phase of the product development cycle - after essential design parameters are already agreed upon for functional prototyping.

Recently, there has been an interest in developing computational design methodologies to make digital manikins to be part of the early design process. For example, Modified Virtual Build Methodology [88] and Human-in-the-Loop Design [82] demonstrated how DHM research enables human factors interventions earlier, on digital models; thus, providing the advantage of assessing human-product interactions prior to physical prototyping. These methods utilized Motion Capture (MoCap) technology to capture human-subject data and validate assumptions for measuring discomfort and joint stresses based on the postural readings. Another computational ergonomics approach is the Virtual Build (VB) methodology, which was first demonstrated by Ford Motor Company. It was proposed as a working platform for integrating Digital Human Models (DHM), MoCap, and Virtual Environment (VE) for ergonomics evaluation of automotive assembly processes before physical fixtures and facilities were constructed [88]. The literature of DHM mainly focuses on developing the DHM software and application of DHM for ergonomic assessment rather than using DHM as a design tool. The following paragraphs present the current literature on the application of DHM, integration of DHM with other domains, and validation of DHM tools.

One of the recent studies showed that DHM was used to design the cockpit of a material handling vehicle. In this research, JACK was used to evaluate the comfort assessment, lower back analysis, and static strength prediction of a driver operating material handling vehicle. After showing that the driver's seat had poor comfort levels in the shoulder and neck area, a new seat design was proposed by adding lateral support and headrest. Also, the dashboard was optimized based on ergonomics outcomes. However, it was not stated in the study what design methodology was perceived during the re-design of the dashboard to optimize the reach zones of the driver [109]. Another recent study demonstrates the application of DHM by evaluating the ergonomics of a large scale retailer's furniture and it's effects on developing work-related musculoskeletal diseases and disorders (WRMSD). The ergonomic assessment of the work-related activities of a clerk and cashier is performed using DHM. It was found that some of the work tasks were not ergonomically sound which increased the risk of WRMSD [209]. Another application of DHM for ergonomic assessment is presented in a study that took place in the wheelhouse on large ships. In this study, the DELMIA manikin software package was used to assess the activities such as visibility, reachability, collision, and comfort of a sailing commander, steersman, and telegraph operator [245].

Another study used DHM to do an ergonomic assessment of sea fisherman's postures adopted during manual handling. 3DSSP was used as the DHM tool and it was found that during sorting and cleaning activity, shear and orthogonal forces acting on lumbosacral level exceeded the recommended limit [208].

A recent study proposed to integrate DHM with lean product development (LPD). The premise is that DHM can be used to do a proactive ergonomic assessment that adds value from the perspective of LPD by reducing the "waste", "overburden" and "unevenness" [120]. [213] proposed how DHM can be used in conjunction with FEA to predict the injury due to repetitive loading. A DHM software named SANTOS was used to calculate the muscle force and motion profile and the data is fed to an FEA model which measured the stresses of the human body joint components. This approach can be used to predict the probability of injury with respect to the number of loading cycles.

Some other studies are found in the literature focus on validating the results of DHM by physical prototyping. For example, [160] compared the ergonomic analysis in a car assembly line between DHM and physical prototype. The study found that in some cases, the differences in the ergonomic assessment between DHM and a physical prototype was small and in some cases it is large. The differences in the results were attributed to the lack of fidelity found in DHM ergonomics tools and oversimplification of the real-world scenarios, such as being unable to take into account the frictional forces. [248] conducted a study to train DHM manikin with baseline information for validation purposes. Outcomes collected from the Safework software DHM platform was compared against the data obtained using electro-mechanical (FARO Arm) and magnetic trackers (Ascension) for a pilot in a cockpit setting. The purpose of this study was to validate the fidelity of Safework ergonomics evaluation tools.

Although the literature demonstrates some of the application and benefits of using DHM in product development, the research on how to incorporate human factors early in the design process still remains limited. A series of recent studies have indicated that designers use DHM primarily as an ergonomic assessment tool rather than an actual design method during the ideation of concepts and exploring the design alternatives [124, 151]. Therefore, a design methodology based on DHM research was proposed in this paper as an alternative medium to visualize and analyze human-product interactions and exploring the design space via computational 3D models for early design ergonomics evaluation of concept designs.

3.3.3 Design Space Exploration

Design space exploration is a method used for gaining more in-depth information about the design problem, design variables, design solutions, and trade-offs. [171] defined design exploration as "the process of generating and evaluating design alternatives that normally would not be considered." Exploring design space is considered a significant characteristic of the conceptual design process [154, 234]. [234] stated that during the conceptual design, it is impossible to get the correct solution in the first try. Thus, the design space should be explored by steps of divergence where multiple design alternatives are generated, and by phases of convergence, the most promising solution is selected [234]. To explore a design space systematically, designers first need simplified models that represent actual environmental or use conditions with sufficient fidelity. Later, various "what-if" scenarios can be executed by altering design variables, and the model responses can be analyzed to make future predictions. Such models, in many conventional design space studies, include experiments on full-scale physical prototypes or Finite Element Analysis (FEA) simulations for predicting outcomes. In this study, we used a surrogate modeling technique with DHM manikins to assist designers in exploring design variants for ergonomics evaluation of concepts, computationally.

3.3.4 Surrogate Modeling Technique

Surrogate modeling is an approximation technique mostly used in design optimization and design space exploration when "what-if" experiments or simulations become time-consuming or sometimes infeasible to conduct within a suitable time due to the increased number of design variables (product attributes) which require excessive amounts of design evaluations. Often, designers use computer simulations to cut cost and time associated with physical experimentation. However, computer simulations also become very expensive and time consuming when exploring a broad design space [125]. For example, within the human-centered design scope, the performance and well-being of the user depend on a broad range of factors such as the work being performed, the posture of the user, workspace conditions, environmental effects, and cognitive workload. Running computer simulations by manually changing all the design points (e.g., the type of work, posture) would be computationally expensive and time-consuming. One alternative is to build an approximate model that can predict the system performance and develop a relationship between the system inputs and outputs [106]. Surrogate modeling technique is an alternative way to express the relationship between the objective function and the design variables with simple form equations. Thus, one can explore regions in the design space for which a solution might not be practically found [34, 125]. The technique has been used in manufacturing, aerospace, and structural analysis studies as a computationally inexpensive method to explore the design space through modeling the responses based on a limited amount of data points chosen from the list of input variables [17, 18, 26, 64].

In this paper, we ran a limited number of DHM simulations that depicted "what-if" human-product interactions happened within different variants of the cockpit model. Then, we used a Kriging-based surrogate modeling approach to predict the response of DHM simulations in other design points. The Kriging model brings the flexibility to create response data with several local extrema and to represent the nonlinear and multi-modal functions [125].

3.4 Methodology

A schematic of the proposed methodology, including the steps of the design work flow, is provided in Figure 3.1.

3.4.1 Problem Definition - Identifying Ergonomics Issues

As shown in Figure 3.1, the proposed design framework begins with identifying problems unique to the ergonomics domain, which potentially affect the operator or user performance. For example, in the context of cockpit packaging, a high-level human-product interaction is present while navigating an aircraft. The performance of the pilot depends on whether the dials on the control surfaces are within reach, any object protruding within the cockpit creates obstruction zones, or sufficient accommodations are provided for easy seat adjustments. Hence, the first step starts with identifying a design problem where the performance of the human operator is adversely affected.

3.4.2 Hierarchical Task Analysis

The second step of the design framework is to identify how users interact with the product/workplace as shown in Figure 3.1. Hierarchical Task Analysis (HTA) is used to identify and examine the tasks that must be performed by a human operator followed by what tasks are needed to be executed [141]. Designers should carefully observe and determine what interactions (e.g., reaching, pulling) are taking place between human operators and components of the product/workplace. In the scenario where the actual product is not available to observe interactions then the designer can talk to experts and users of similar products to determine the interactions. A good example of HTA can be found by analyzing the interactions of a pilot in the cockpit. The task of landing an aircraft can be broken into subtasks (e.g., reaching thrust level, reducing throttle) to identify what human actions (e.g., reaching thrust level) and components (e.g., thrust level) need to be focused during the concept development. At this step, designers should search the model to identify a list of critical design variables that can affect the human-product interactions.

3.4.3 Workplace Simulation

Performing HTA and understanding which human-product interactions to focus on is a crucial step to identifying what part of the product/workplace should be modeled and simulated. After HTA is completed, computational representation of the product, workplace, and the human manikin is built using CAD and DHM integration. The digital manikin representing the actual user which is created via anthropometric libraries in DHM software, and 3D models of the workplace/product build via CAD. After the CAD data is loaded into the DHM framework, posture manipulations, predefined motions, and inverse kinematics modules within the DHM are used for setting and simulating the human-product interactions taken from the HTA in Step 2. Ideally, a MoCap system can be synced with DHM if high-fidelity human task motion data is needed. However, a MoCap setup is often not the desired solution during the product conceptualization stage due to additional time and cost requirements. Next, human performance measures based on musculoskeletal, biomechanics, and vision analysis are generated based on the simulation data. The simulations are categorized into two parts, as shown in the highlighted area in Step 3. In the first set of simulations, one design variable is changed at a time to find out the effect in ergonomic performance. Critical design variables are identified by statistically analyzing the data obtained from the first set of simulations. Next, the second set of simulations are performed to generate data that is used to construct the surrogate models as shown in Figure 3.1. The statistical analysis and surrogate model is explained in Step 4.

3.4.4 Statistical Analysis and Surrogate Modeling

The first part of Step 4 focuses on analyzing the data gathered from Step 3 to identify which design variables significantly affect the ergonomic performance. Statistical methods, including parametric or non-parametric analysis techniques, are used for determining the type of relationship between the design variables and human performance. Further, the same data is used to test statistically significant relationships. If no statistically significant design variables are found, then Steps 2 to 4 are iterated as shown in Figure 3.1.

Once the critical design variables are identified, a surrogate model is built in the second part of Step 4. A Design of Experiment (DoE) determines the sample points or the number of simulations needed to create the surrogate model. For example, in this study, a Latin Hypercube Sampling method [163] was used for generating the sample points where all the design variables were changed simultaneously. A surrogate model was built for each manikin using the second set of simulation data gathered in Step 3. At this stage, the relationship between the critical design variables and their responses are established. In other words, dependent variables are expressed as a function of one or more independent design variables.

3.4.5 Design Exploration

In the fifth step, design exploration is performed as shown in Figure 3.1. The surrogate modeling approach assists designers to explore how each design variable can affect the response, i.e., human safety, comfort, and performance. Optimization techniques can be used to improve the surrogate model by either maximizing or minimizing desired safety, comfort, or performance parameters. At this stage, with the help of the surrogate model, designers can explore the design space via monitoring whether the human performance is within the permissible limits. For example, a designer can explore whether choosing a range of one or more design variables improves the ergonomics response (e.g., reach envelope) while adversely affecting another measure (e.g., the risk of injury in L4/L5 –vertebrae in the lumbar spine). The optimization of the surrogate model allows designers to find the value of design variables that provides better human performance measures. Additionally, if there are multiple performances to be maximized, then designers can prioritize specific performances and create multiple design alternatives.

3.4.6 Validation

The results obtained in Step 5 from optimizing the surrogate model can be evaluated either computationally or by building low-fidelity physical prototypes with only a small set of pilot human-subject data collection. Since the surrogate modeling approach is based on meta-models that only approximate the real experimental or simulation model, results from the surrogate model analysis are validated here, computationally, by keeping DHM and CAD models as references.

The specific set of design variables that provides optimal performance identified in Step 5 are used for creating the workplace layout in CAD. Then, the CAD model is exported in DHM to observe human performance. As can be seen in Figure 3.1, the optimal design variables are fed to Step 6 for validation purposes. The surrogate model is validated if the observed performance in DHM is in close agreement with the performance value obtained from Step 5. However, if the performance results are not in close agreement, then the Steps 3 to 6 are reiterated, as shown in Figure 1.

3.5 Case Study

A review of the capabilities of DHM, CAD, and surrogate modeling techniques were provided in Section 2, and a description of the proposed methodology was summarized in Section 3. In this section, a cockpit packaging study is presented to demonstrate how the proposed design methodology is applied in the cockpit layout design study.

3.5.1 Step 1: Design Problem

The cockpit packaging evaluation of the Boeing 767 cockpit focused on reachability, accessibility, and obstruction related ergonomics performance measures. The design of the instrument panel and the pilot's seat position was chosen as critical cockpit elements, which included multiple levels of design variations. The instrument panel conceptual design variations included changes in the curvature, tilt angle, and height. The design parameters for the pilot's seat position included the horizontal and vertical distance from the instrument panel and cockpit floor, respectively. The changes associated with the cockpit packaging were made so that the instrument panel was within the reach envelope and the pilot had a maximum field of vision - targeting the cockpit windshield. This cockpit packaging model was set to accommodate extremities in the anthropometry, from 5^{th} female and

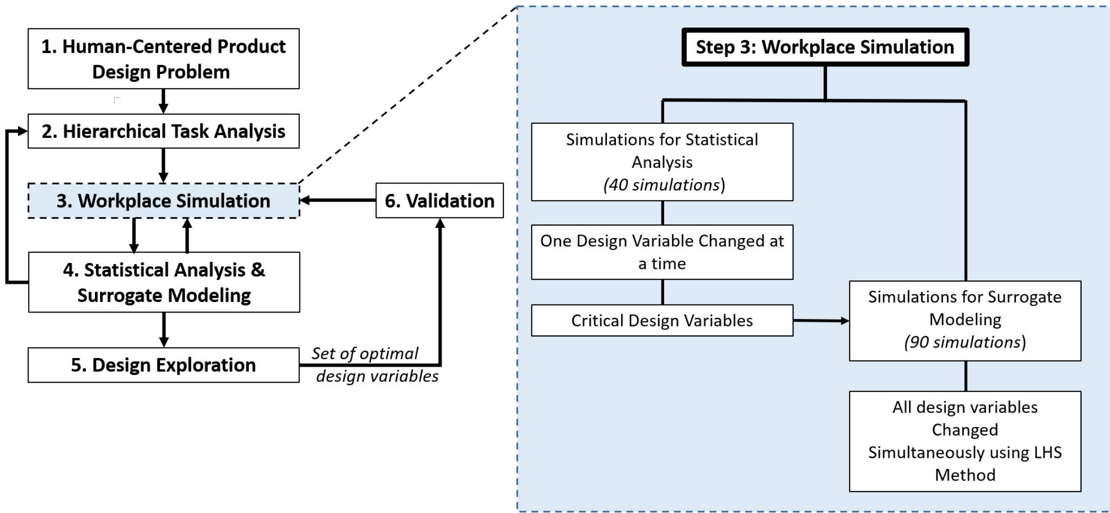


Figure 3.1: Methodology of the Design Process adapted from [16]

95^{th} male manikin.

3.5.2 Step 2: Hierarchical Task Analysis

The second step in the proposed design methodology is to perform HTA to understand how the users/operators interact with the product or workplace. A snippet of HTA developed for Task 3.0 (Prepare the aircraft landing) is shown in Figure 3.2, including some sub-level tasks that involve in landing an airplane. The high-level HTA for the landing procedure included the pilot to confirm the visibility of the runway visually and change the flap settings, as shown in Tasks 3.1, 3.3, and 3.8 in Figure 3.2. The HTA analysis provided in Figure 3.2 indicates that having an unobstructed vision and having the instrument panel within the reach zone were the must-have accommodations used during the DHM simulation setup.

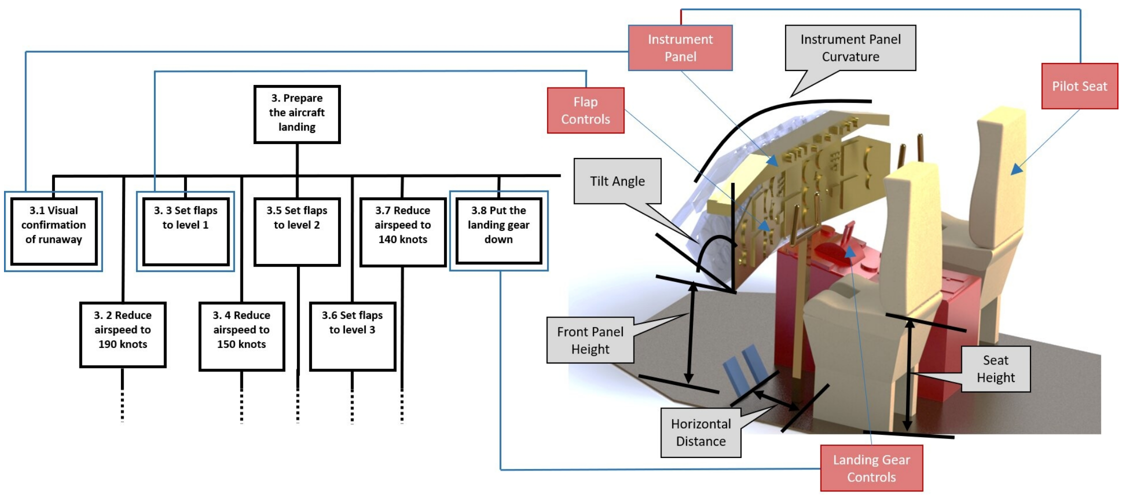


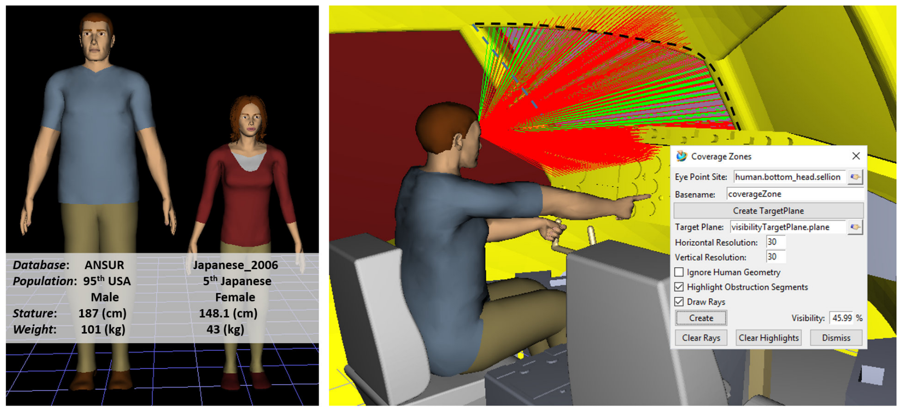
Figure 3.2: A simplified Hierarchical Task Analysis (HTA) of the pilot-cockpit interactions during descend - moments before the touchdown [113] and CAD model of Boeing 767 cockpit

The high-level critical tasks associated with the landing procedure are circled in red and are simulated in Step 3.

3.5.3 Step 3: Simulating the Workplace

The third step of the design framework is to build the CAD model of the cockpit with sufficient detail to represent the pilot-cockpit interaction as found in HTA. Task 3.1 in HTA involved the pilot having an unobstructed vision through the windshield so that he/she can check the distance from the runway. The geometry of the instrument panel and location of the pilot seat might affect the vision; hence, Task 3.1 was connected to the instrument panel and pilot seat. Similarly, the dashed lines that are connecting the HTA Tasks 3.3 and 3.8 with the cockpit elements are also represented in Figure 3.2. The CAD model was then exported into a Siemens Jack DHM software where desired "what-if" simulations regarding what tasks the pilot needed to go through, such as reaching the instrument panel and looking through the cockpit windshield, was simulated computationally. The simplified concept CAD model of the Boeing 767 cockpit layout consisted of: pilot seats, a pedestal (middle console) includes the thrust level and throttle controls, a forward instrument panel (concave with respect to the pilot) with essential dials and controls, and a yoke for flight controls (Figure 3.2). In this study, instrument panel curvature, height, and tilt angle, as well as the horizontal and vertical distance of the pilot's seat configurations, were defined as design variables (Table 3.1) that the designer had the freedom to iterate/change during the conceptual design stage. For example, the designer had the freedom to create concept cockpits with the instrument panel tilt angle that was ranging between 0 degrees and 30 degrees. Because our design approach focused on the conceptualization and early phases of product development, a low-fidelity CAD model was constructed, which still was able to display critical cockpit elements with sufficient fidelity.

In this study, the ergonomics accommodations provided in the concept model were based on the human factors packaging principles, which suggests the clearance for the largest user and the reach for the smallest user. This principle allows the consideration of the extremities (the largest and smallest percentage of pilot anthropometry) in a target population early in the conceptualization stage [238]. Working with the extremities in the population ensures that a wide range of anthropometric differences (e.g., stature, weight) can be accommodated during the



(a) (b)

Figure 3.3: (a) A 95th Percentile USA male and 5th Percentile Japanese female constructed through the ANSUR and Japanese_2006 anthropometric libraries (b) Reach Gap and Vision Obstruction analysis is performed within Siemens Jack 9.0

concept cockpit package re-evaluation. The Anthropometric Survey of U.S. Army Personnel (ANSUR) and Japanese_2006 anthropometric libraries were used to construct a 95^{th} percentile U.S. male and 5^{th} percentile Japanese female manikin to represent the extremities of anthropometry within the subject pool (Figure 3.3(a)).

Table 3.1: The design performance objectives and the maximum and minimum limits of the cockpit design variables used in this study

Design Objectives	**Minimize Reach Gap** **Minimize Vision Obstruction**	
Design Variables	**5^{th} Percentile Japanese Female**	**95^{th} Percentile U.S. Male**
Instrument Panel Curvature	0-10 (degree)	0-10 (degree)
Instrument Panel Height	47-75 (cm)	47-80 (cm)
Instrument Panel Tilt Angle	0-30 (degree)	0-30 (degree)
Horizontal Seat Distance	28-33 (cm)	45-55 (cm)
Vertical Seat Height	34-47 (cm)	34-53 (cm)

After the manikins were created and positioned with reference to Hip-point and feet on the pedals, tasks derived from the HTA were simulated within the DHM software. For example, the task "prepare the aircraft landing" taken from the HTA in Figure 3.2 contains a sequence of sub-tasks (activities), including confirming the visibility of the runway through the front and side cockpit windshields (Task 3.1), reaching the instrument panel and setting flaps to a specific level (Task 3.3 and 3.5). These sub-tasks were broken into more sub-levels that were associated with the physical and cognitive activities that pilots often need to execute while operating an aircraft. Only a snippet of the activities was provided here to demonstrate how HTAs were used for constructing human-environment simulations within the DHM framework.

In Step 3, ergonomics assessments were divided into two parts (Figure 3.1). In the first part, the five design variables were changed one at a time to measure the pilot's ergonomics performance (reach gap and vision obstruction). A total of forty simulations were executed to run the statistical analysis. Then, the performance data was analyzed to determine which variables were statistically significant. In the second part, only the critical design variables that were found to be statistically significant were changed simultaneously using the Latin Hypercube Sampling (LHS) method, and the performance outcomes were measured. A total of ninety simulations were executed. The data collected was used for creating the surrogate models for each manikin.

Throughout this research, DHM simulations were performed using Siemens

JACK9.0 software [42]. Figure 3.3(b) shows vision obstruction and reach performance evaluations rendered in Siemens JACK. In this figure, one can see that a 95^{th} percentile U.S. male manikin created from ANSUR anthropometric library database was working on tasks derived from the HTA in Setup 2, which included a reaching task (Task 3.3 and 3.8) and visual inspection task (Task 3.1). In this DHM simulation, the manikin (pilot) attempted to reach a predefined control button located on the front instrument panel with the right-hand index finger while holding the yoke with the left hand and controlling the rudder with both feet on the pedals. A reach analysis toolkit based on the inverse kinematics was used for measuring the gap between the tip of the right-hand index finger (distal phalanx) and the control button surface that is located normal to the manikin. Also, vision obstruction analysis was performed using the vision coverage toolkit to measure the percentage of the unobstructed visual field. The vision coverage analysis toolkit measures the percentage area of the whole binocular visual field that is not occluded/blocked by the cockpit elements. The percentage area is measured by computing how much of the rays leaving the eye-center (between-eyes) of the manikin reaches a target plane. Thus, percent vision obstruction can be calculated by subtracting the percent vision loss from the perfect vision coverage (100%). In Figure 3.3(b), the dotted plane located right behind the windshield illustrates an artificial target plane that defines an area of interest (left portion of the windshield). Cockpit elements highlighted in yellow illustrate the areas that obscured manikin's binocular visual field.

One of the causes of the inconsistencies in DHM simulations is the manikin positioning and posture setup with manual input (mouse clicks) [214]. To achieve consistency in DHM task evaluations, all the simulations that were performed in this study followed the following standardized setup protocol. Each manikin is restricted with an initial coordinate and sitting posture using the pilot's seat as a reference. Thus, the changes in cockpit design variables did not affect the initial sitting position and posture of the manikin. No matter what cockpit layout was built, this approach ensured that the manikin was able to maintain the recommended standard flight control posture, (i.e., hands-on the yoke, foot on rudder panel). In addition, sufficient knee clearance, from the instrument panel to the knees, was provided for manikins throughout the simulations when generating data points with the Latin Hypercube Sampling method.

3.5.4 Step 4: Statistical Analysis and Surrogate Modeling

The fourth step of the methodology is split into two parts. The first part focused on identifying the critical design variables, which had significant effects on the ergonomics performance. As mentioned in Step 3, each design variable was changed one at a time, and the corresponding performances were measured. The sample points for each design variables were chosen randomly. It was found that eight sample points produced statistically significant results (based on p- and R-values) as shown in Table 3.2. Hence, eight sample points for each of the five design variables produced forty DHM simulations, as shown in Figure 3.1.

Figure 3.4 represents how the design variables affect the pilot's performance

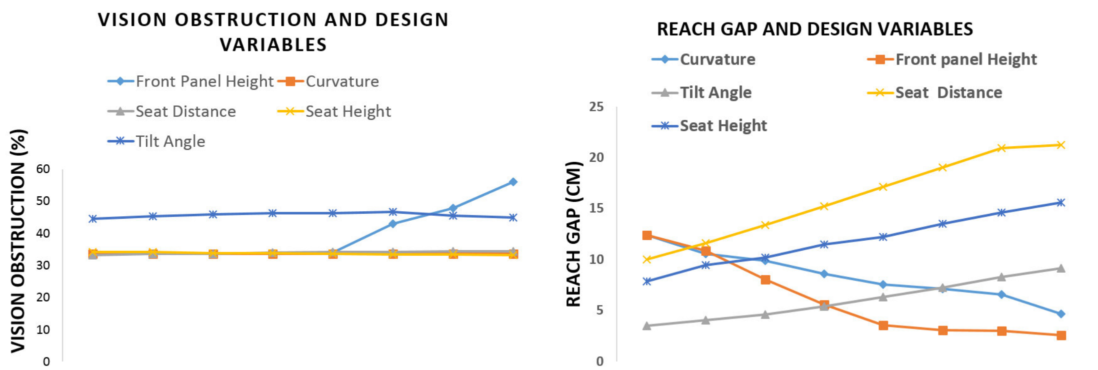


Figure 3.4: Percent vision obstruction outcomes with changing design variables one at a time and Reach gap outcomes with changing design variables one at a time.

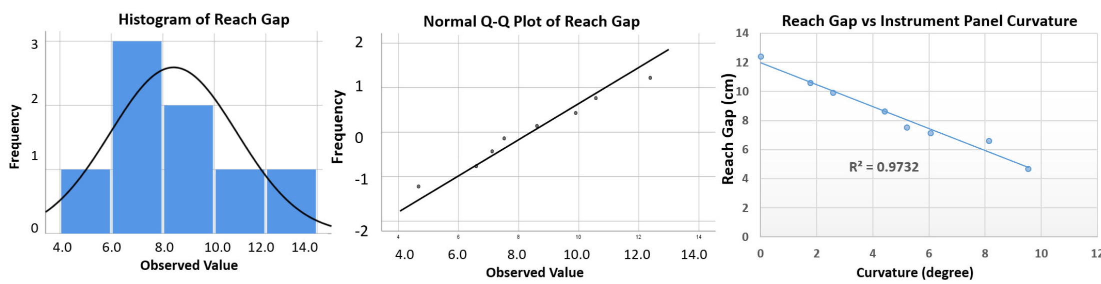


Figure 3.5: Normality Test and Curve Fitting for Reach Gap

for percent vision obstruction and the ability to reach the predefined location. For example, Figure 3.4 shows that the reach gap increases as the horizontal seat distance, vertical seat height, and tilt angle of the instrument panel are increased. Conversely, the reach gap decreases as the instrument panel curvature, and height is increased. Similarly, Figure 3.4 illustrates the relationship between design variables and percent vision obstruction outcomes. For example, the vision obstruction and front panel height are positively correlated.

Table 3.2: Summary of the statistical significance results for design variables.

Design Variables (DV)	Performance	
	Reach Gap	**Obstruction**
1) Instrument Panel Curvature	R=0.987, p-value= 0.0001	No Relation
2) Instrument Panel Height	R= -0.937, p-value=0.0001	R= 0.881, p-value=0.004
3) Instrument Panel Tilt Angle	R=0.994, p-value=0.0001	R= -0.260, p-value= 0.553
4) Seat Distance	R= -0.995, p-value=0.0001	R= -0.961, p-value=0.0001
5) Seat Height	R= 0.998, p-value=0.0001	R= 0.967, p-value=0.0001

A graphical representation of the responses helps designers to capture the trends between design variables and the ergonomics outcomes; however, an oversimplified visual illustration does not reveal whether the design variables are statistically significant. Statistical analysis such as the Pearson Correlation test can show the relationship between two variables. First of all, the normality assumptions were checked on the raw data before conducting the Pearson Correlation test. The results of Shapiro-Wilk's test (p greater than 0.05) and visual inspection of the histograms and normal Q-Q plots showed the dependent variables (i.e., Reach Gap and Vision Zone values) are approximately normally distributed [206]. A sample of Histogram and Q-Q plot for checking normality is given in Figure 3.5. Figure 3.5 shows that the histogram is closely in a bell-curve form, and the points fall on the line in Q-Q plots suggest normality.

After the normality assumptions were checked, we performed Pearson Correlation analysis and calculated the p-values to detect which design variables had significant effects on the performance - ergonomics outcomes. A sample curve fitting of the reach gap is shown in Figure 3.5. Also, the list of p-values and R-values are provided in Table 3.2.

Table 3.2 shows the strength of the correlation between the design variables and the performance using Pearson Correlation R-values, ranging from -1 to +1. A minus sign indicates a negative correlation, whereas a positive sign indicates a positive correlation, and the closer the value is to unity, the stronger is the correlation. Table 3.2 shows some of the design variables have either positive, negative, or no correlations indicating that these variables can either improve, deteriorate, or do not affect the human performance. Also, all of the R-values are close to unity, which shows that the design variables play a substantial role in human performance within the cockpit packaging scenario. The p-values indicate the significance level of the R-value. If the p-value is smaller than 0.05, then the design variable is statistically significant at a 95% confidence level. Table 3.2 shows all of the p-values are smaller than 0.05; thus, the majority of the design variables show strong positive correlation and are statistically significant except the instrument panel curvature and instrument panel tilt angle in relation to the vision obstruction performance. This indicates that when the design variables, such as instrument panel curvature and instrument panel tilt angle, are changed one at a time and within the specified range as shown in Table 3.1, the vision performance is not affected. Even though the analysis indicates that the instrument panel curvature and the tilt angle are not significant, we have included these two design variables along with the remaining three design variables to create the surrogate model. It is because in the surrogate model all the design variables were changed simultaneously to see the effect on human performance whereas the analysis in Table 3.2 was based only on changing one design variable at a time.

The second part in the fourth step was to create two surrogate models using the data points created via the Latin Hypercube Sampling method [163] as shown in Figure 3.1. Latin Hypercube Sampling method considered all the design variables simultaneously when observing the human-product interaction in DHM. As two manikins (male and female) coming from different anthropometries (the U.S. and Japanese) were used in this study; thus, two sets of sample points were constructed using the Latin Hypercube Sampling method. Each set of sampling contains forty-five points in which totals to ninety simulations as shown in Figure 3.1 so that the entire design area was covered. Forty-five samples were chosen so that there were enough sample points to create a close enough surrogate model while not being computationally expensive. We used Kriging approximation to estimate a response surface of the performance outputs from a relatively small number of simulations performed in DHM. Within the Kriging surrogate model, a Gaussian correlation process was used in finding the optimal values [125, 233]. The Design and Analysis of Computer Experiments (DACE) within the MATLAB software package were used to construct a Kriging approximation model based on the collected DHM simulation data, and to use the approximation model as a surrogate for the human performance measures [156]. The surrogate model based on the Kriging approximation approach represented the unified effect of the design variables on human performance.

In the next section, the cockpit design space is explored by optimizing the surrogate models. The results obtained from the surrogate model delivers the value of each design variable that produces optimum human performance.

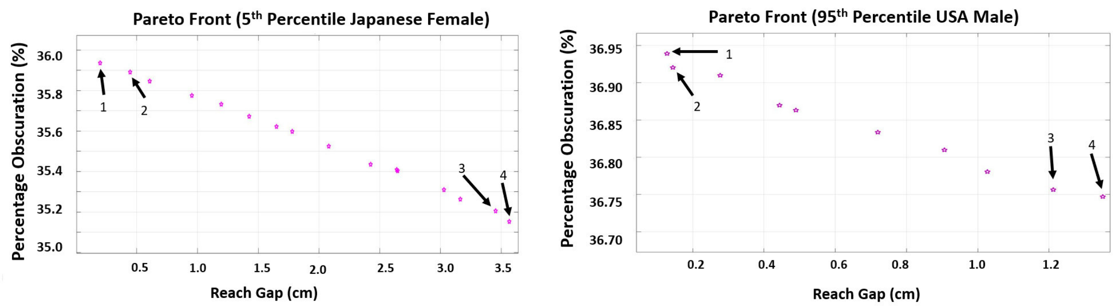


Figure 3.6: Pareto front of the Reach Gap and Vision Obstruction for the 5th and 95th percentile Japanese female and USA male

Table 3.3: Optimal reach zone and percent obstruction performance for the 5th percentile Japanese female and 95th percentile US male manikins.

		Design Variables						Performance	
Pilot	Point	Curvature	Height (cm)	Tilt Angle	Seat Distance (cm)	Seat Height (cm)		Reach Gap (cm)	Obstruction (%)
5th Percentile Japanese Female	1	9.98	54.97	8.60	32.46	33.77		0.20	35.94
	2	9.98	55.82	9.19	32.45	33.80		0.45	35.89
	3	9.87	56.76	19.86	32.45	33.73		3.45	35.20
	4	10.00	57.01	20.55	32.45	33.73		3.57	35.15
95th USA Male	1	7.17	59.12	6.96	47.22	34.13		0.13	36.94
	2	7.71	58.76	6.93	46.97	34.10		0.14	36.92
	3	7.09	57.89	8.02	46.61	34.15		1.21	36.76
	4	6.98	57.73	8.14	46.61	34.22		1.35	36.75

3.5.5 Step 5: Design Space Exploration

The surrogate models used in this study are explored using the Genetic Algorithm in MATLAB Global Optimization toolbox. The objective of the model was to minimize the reach gap and minimize the vision obstruction for a given set of design variables with two pilots representing different anthropometric backgrounds as shown in Table 3.1. The resulting Pareto fronts of this multi-objective optimization for both 5^{th} and 95^{th} percentile female and male are given in Figure 3.6.

The Pareto front analysis in Figure 3.6 shows that as one of the performance parameters (reach gap) is improved, the other performance parameter (percentage obstruction) deteriorates. For example, Figure 3.6 shows that the optimum reach zone, denoted by point 1 and 2, has the highest percent obstruction, and points 3 and 4 has the least percent obstruction but maximum reaching gap. The Pareto front values show how a specific performance is changing when another performance is improved or worsened. In this case study, it was observed that the performance of the reach gap was contradictory to the performance of vision. The corresponding design variables of the points 1 to 4 from Figure 3.6 are presented in Table 3.3. The designer can now decide whether to treat one performance of higher value than the other or can treat them equally based on values in Table 3.3. The designer can use these design variables and create a cockpit that would yield the desired performance measurements. If the designer is interested in exploring how a particular design variable affects the pilot performance, analyses presented in Figure 3.4 and Table 3.2 can be used to estimate performance outcomes. Alternatively, if the designer is interested in cockpit configurations that yield optimal human performance, then the data in Table 3.3 can be used where all the design variables are considered simultaneously.

In addition to estimating how each design variable affects the performance or finding out the optimal cockpit configurations, designers can also explore how the cockpit configurations change due to different populations' needs. For example, Table 3.3 shows that the instrument panel curvature values for the 5^{th} percentile Japanese female are higher than that of the 95^{th} percentile U.S. male. This is because the 5^{th} percentile female has shorter arm length compared to the 95^{th} percentile male; thus, an instrument panel with increased curvature allows the

Table 3.4: Comparison of performance outcomes of HTA simulations executed with surrogate modeling approach and digital human modeling approach

Table 3 Points	**Reach Gap (cm)**		**Vision Obstructed (%)**	
	Surrogate Model	**Digital Human Modeling**	**Surrogate Model**	**Digital Human Modeling**
Male 1	0.13	0.10	36.94	37.05
Male 4	1.35	1.09	36.75	37.20
Female 2	0.45	0.32	35.89	36.80
Female 1	0.20	0.18	35.94	37.04
Mean diff.	0.11		-0.64	
t- value	0.30		2.26	
p-value	0.77		0.06	
95% CI	-0.77 to 0.99		-1.13 to 0.05	

5^{th}percentile female to reach the control knobs on the instrument panel. Similarly, the seat distance readings from the instrument panel to the seat column are higher for the 95^{th} percentile male as compared to the 5^{th} percentile female because the higher the anthropometric percentile in population the more the leg or knee room should be accommodated.

3.6 Validation

Step 6 of the methodology described in this study (Figure 3.1) consists of validating the surrogate model and the optimization results. The validation is done by comparing the performance measures from DHM simulations to the performance obtained from the surrogate model for the exact set of design variables. The validation analysis required re-creating scenarios presented in Table 3.3 within the DHM environment, including manikins and CAD models, and noting whether there are differences in performance outcomes. The design variable values presented in Table 3.3 were used to configure (re-create) cockpit concepts in DHM software. Next, simulations were performed in DHM to record reach gap distances and percent vision obstructions. The performance outcomes obtained from DHM simulations were compared with the performances obtained by the optimization.

An independent-sample t-test is used for validating the performances obtained from surrogate modeling (SM) and DHM. The hypothesis is as follows:

H_0: $\mu_{SM_{performance}} = \mu_{DHM_{performance}}$
(no effect of SM and DHM approach on human performance)

H_1: H_0 is rejected

Hypothesis: For each subject, the mean performance (reach zone and percent vision coverage/obstruction) outcomes with surrogate modeling (SM) and Digital Human Modeling (DHM) approach are not significantly different.

Random data points (Male 1 and 4; Female 1 and 2) from Table 3.3 are selected for validation against DHM as shown in Table 3.4. Table 3.4 shows the independent-sample t-test of the performance results obtained from optimizing the surrogate model approach (Table 3.3) and the DHM approach. The mean difference between the surrogate model and the DHM group is 0.11 and -0.644, respectively. The t-value is small, and all p-values are larger than 0.05, which presents that there is not enough convincing evidence to reject the null hypothesis. Hence, the performance results obtained from the surrogate model are equal to the results obtained from the DHM model for the same set of design variables.

3.7 Discussion

A design space exploration methodology is presented in this paper to proactively integrate human factors early in the conceptual design before any major design decisions or resource allocations are made. The computational approach discussed in this research allows designers to explore product design space in terms of human factors attributes. One of the advantages of this study is its flexibility of simulation "what-if" scenarios based on CAD models with DHM, which enables the exploration of design alternatives before physical prototypes are built. This is especially important for design studies where human-subject data collection is limited or it's associated with the increased risk of injury or hazard.

The design approach discussed in this research allows designers to explore design space to find cockpit configurations that optimize the performance of users coming from different anthropometries. The proposed methodology uses digital iterations on the CAD models with DHM manikins; thus, creating a proactive human factors engineering assessment framework for design exploration without relying on physical cockpit prototyping or human subject data collections. Using this design approach, designers can identify what the critical design variables are and the degree of how design decisions affect human performance. Only a limited set of design variables and performance outcomes are used in this paper to present the design methodology. One can increase the number of design variables and performance outcomes to identify optimum configurations of the cockpits or prioritize one performance outcome over others either for a specific user or a range of users coming from different anthropometric backgrounds.

As discussed in the Introduction section, many HFE interventions that require expensive prototyping and time-consuming human subject data collection add extra financial burden and delays on the overall time-to-market. Often, designers put more emphasis on the other technical aspects of product development and do not put adequate emphasis on some of the core fundamental HFE evaluations. Besides, many designers are not well informed about the emerging computational methods within the HFE domain and often do not make HFE a core element of the early design process [139, 243]. The surrogate modeling approach with the DHM research offers a time and resource-effective alternative to the conventional reactive ergonomics methodologies. The computational approach presented in this research does not require an HFE specialist to be present to run experiments and evaluate early design concepts. Instead, running task simulations with concept product models in DHM can bring the advantage of iterating design concepts digitally.

One of the significant contributions of this research to the DHM domain is that the design methodology proposed in this paper utilizes DHM as an actual design method rather than just an ergonomic assessment tool. DHM is often used as a computational alternative for running quick and low-fidelity ergonomics evaluations on manual material handling tasks and in the design of relatively simple products. In this paper, DHM was not used just to assess a final product but rather it was used as an actual design method to inject human factors during the early conceptualization of the product or workplace.

3.8 Limitations and Future Work

A simplified HTA is used to summarize high-level pilot-cockpit interactions. A very detailed pilot-cockpit interaction would have given a complete picture on how the pilot is interacting with the instrument panel and the rest of the components of the cockpit; however, this might have added a lot more design variables and analyses which goes beyond the purpose conceptualization and the scope of this research study. In this paper, we demonstrated only the feasibility and efficacy of the design approach. In addition, only a computational validation was provided in this paper. An exhaustive validation study needs a comparison between the result obtained from the surrogate modeling approach and results gathered from an experimental study, which includes a functional cockpit prototype with human-subjects going through actual HTAs within a flight-simulator setup. We plan to carry out a validation of our framework in a follow-up study.

Another potential future work that comes after validating the proposed approach is to perform a study to understand the suitability of the DHM and surrogate modeling with respect to the human-product interaction. The goal of the study will be to compare the feasibility of using low- (CAD and DHM) and high- (CAD, DHM, and surrogate modeling) fidelity prototypes in modeling low and high human-product interactions.

Chapter 4: Prototyping Human-Centered Products in the Age of Industry 4.0

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4.1 Abstract

Industry 4.0 promises better control of the overall product development process; however, there is a lack of computational frameworks that can inject human factors engineering principles early in design. This shortage is particularly crucial for prototyping human-centered products where the stakes are high. Thus, a smooth Industry 4.0 transformation requires keeping ergonomics in the loop, specifically to address the needs in the digitized prototyping process. In this paper, we explore a computational prototyping approach that focuses on various fidelity levels and different human-product interaction levels when conducting ergonomics assessments. Three computational prototyping strategies were explored, including (1) a digital sketchpad based tool, (2) computer-aided design and digital human modeling based approach, and (3) a combination of computer-aided design, digital human modeling, and surrogate modeling. These strategies are applied to six case studies to perform various ergonomics assessments (reach, vision, and lower-back). The results from this study shows that the designers need to consider the trade-offs between the accuracy of ergonomic outcomes and resource availability when determining the fidelity level of prototypes. Understanding the intricacies between the fidelity level, type of ergonomic assessment, and human-product interaction level helps designers in getting one step closer to digitizing human-centered prototyping and meeting Industry 4.0 objectives.

Keywords: Industry 4.0, prototyping, human-product interaction, digital human modeling, product design

4.2 Introduction

The engineering community is in the midst of a rapid transformation of how the product is designed and manufactured. Over the last few years, significant advancements in computers, sensors, and communications technologies have accelerated hyper-connected smart design and manufacturing systems. With this shift, engineering practices have moved towards considering the entire product life-cycle in addition to production aspects during the manufacturing process [203]. At the heart of this technology-driven transformation, digitization via the exponentially growing technologies (e.g., Internet of Things (IoT), automation, additive manufacturing) are paving the way for cyber-physical systems design—merging the real and virtual worlds.

The above trend is often regarded as Industry 4.0 and has been used across Europe, particularly in Germany's manufacturing industry since around 2010. Around the same time, North American industries adopted a similar production practice called "Industrial Internet" [153]. Likewise, France and China introduced "Industrie du futur" and "Made in China 2025" respectively [12,13]. Today, Industry 4.0 is both an inspiration and opportunity for global competitiveness [38, 195] as many refer to it as the fourth industrial revolution. Thus, it is expected that Industry 4.0 will bring a significant shift in the industry by incorporating digitization of production, automation, and linking manufacturing plants with supply chain [29, 194, 204]. The definitions, key concepts, core technologies, and ways of implementing Industry 4.0 practices are continuously evolving [35, 73]. The

Industry 4.0 needs an advanced architecture that is highly technologically complex, which is why it is yet to reach maturity in terms of solving broader technical problems [63, 148]. Industry 4.0 requires further research on the theories and implementations from multidisciplinary domains such as customization, optimization, automation, decisions support, human-machine interaction, and digitization [73, 185, 194, 235]. In addition to studying the broader scope, it is also vital for engineers to explore the building-blocks or particular elements (cogs in the wheel) that make up the whole to meet Industry 4.0 goals [157]. One such cog that has a critical role in designing modern products is the computational models that enable better early design prototypes.

Prototyping, and important phase of product design, is known to be resource-hungry (time, cost, material, machines, and personnel) [21]. As a result, prototyping significantly impacts the overall production [21]. This paper introduces a computational prototyping study where the fidelity levels and human-product interaction levels are explored to identify their effects in prototyping human-centered products. Identifying and understanding the intricacies between the fidelity, interaction level, and ergonomic assessment will help to build an effective computational prototyping approach that can be a key facilitator to meeting Industry 4.0 goals. The computational prototyping approach highlights the centrality of design by injecting computational ergonomics workflows that allow designers to capture human-product interaction related issues early in design before functional prototypes are built. This approach overlaps with the premises discussed within Industry 4.0 by focusing on customer-oriented mass customization, simulating human-machine interactions early in design, and injecting human factors throughout the value-chain; thus, improving the efficiency of product development [78, 100, 157]. The human-centered prototyping approach discussed in this paper has the potential to aid design companies in reducing the overall design time and cost, and improving other factors such as quality, risk, and overall environmental sustainability. The main contribution of the paper is to build a building block for a computational prototyping approach focusing on injecting ergonomics in human-centered products. This computational approach will help in the digitization, consideration of ergonomics, and in the overall product design process in the age of Industry 4.0.

The road-map of the paper is as follows: Section 2 presents a literature review on the building blocks of the prototyping methodology: (a) prototyping in the human-centered design domain and (b) digital human modeling (DHM). Section 3 talks about the prototyping methodology and presents a case study for illustrating the research objectives. Section 4 and 5 contain results and discussions, and Section 6 wraps up the study by summarizing the limitations and future work.

4.3 Background

Many studies have shown that injecting ergonomics early in design (a proactive approach before risky events occur) enables designers to implement human factors engineering (HFE) guidelines better to mitigate potential risks, allowing the development of ergonomically sound products or workplaces [210]. Hence, the proactive ergonomics approach provides designers a better strategy to develop products that are improved in quality by encompassing human-product interactions as an essential part of the continuous improvement process, not as a one-time event. Also, eliminating retrofitted design changes decreases the lead-time to market and requires fewer resources [170].

Incorporating HFE guidelines during product development involves collecting human-product interactions data, which is often not widely available [95]. Alternatively, designers can utilize prototyping as a method to simulate human-product interaction by creating either a physical prototype, computational prototype, or mixed prototype. Physical prototypes are advantageous in representing form and functionality; however, they are time-consuming and costly to build [40, 47]. In contrast, computational prototypes are low-cost and faster to develop; however, they lack the fidelity in representing physical interactions between human operators and products, limiting the extent of feedback [51, 142]. Another concern during prototyping is the level of interaction between the user and the product. Duffy (2007) mentioned that a physical prototype would be a better choice if there is a high-level interaction between the user and the product. In contrast, when a low-level interaction exists, a computational prototype is preferable [88].

Depending on the level of interactions (e.g., from low to high) between the users and products, designers need to agree on the type (physical or virtual), fidelity (low or high), and complexity (low or high) of the prototypes before the embodiment phase starts. However, there is a lack of understanding and guidelines on systematic prototyping solutions that can help designers navigate the above considerations. This work aims to explore the intricacies between the fidelity level, human-product interaction and ergonomic assessment level in a computational prototyping approach [19]. This association can support designers in creating more effective prototypes for human-centered products to evaluate ergonomics in the early phases of the design process. The overall approach also supports the Industry 4.0 objectives, within the scope of the cyber-physical systems, by utilizing sensors and virtual reality data to inform DT-driven early design ergonomics decision making.

In this paper, human-product interaction is defined by borrowing the concepts from human-computer interaction (HCI) and human-robot interaction (HRI). The interaction between the human and system is regarded as actions that the human operators perform to a system and the feedback that the operator receives from the system. The interactions in this context can be either complex or simple, depending on the number of actions and feedback that are present. In this research, three computational prototypes of low-, mid-, and high-fidelity levels are used to prototype and evaluate the ergonomic assessment of six conceptual products having low, mid and high human-product interaction levels.

4.3.1 Prototyping in Human-Centered Design

In the human-centered design (HCD) domain, one of the critical aspects of employing prototyping activities is to detect HFE design issues that can negatively affect the product's overall performance and the well-being of the user. One can see in the literature that various attempts have been made to develop prototyping taxonomies that aid designers in planning prototyping strategies systematically. Multiple taxonomies have been classified in terms of cost, stage of design, level of abstraction or realism, and intended evaluation purpose [177, 179]. Prototyping classification has also been made based on the process used to create a prototype, such as material removal or material addition [252]. One of the shortcomings in these classification approaches is the lack of broad coverage of the prototyping design space [212]. A more comprehensive taxonomies of prototyping, which was developed based on variety (physical or computational), complexity (system or component), and fidelity (high or low) [133, 212, 219], served as the foundation for the prototyping studies used in this paper.

There are various advantages and disadvantages for each type of prototype. Physical prototyping is an effective strategy when designers want to evaluate the shape composition and functionality of a product [47,112]. Three-dimensional (3D) physical prototypes are best at representing the shape relations and providing visual and tactile feedback [46]. In traditional ergonomics studies, the standard industrial practices involve building physical prototypes and conducting human subjects experiments to evaluate operator performance [28]. However, physical prototypes take a long time to build; they are inflexible to modifications, and costly [40]. Alternatively, computational prototypes can be built quicker. They are easier to share and transfer between different parties involved in the design process because there are no shipping and handling concerns. Additionally, a computational prototype's flexibility allows it to be used repetitively without creating a new prototype every time a design change is made [51]. These characteristics enable computational prototypes to be built faster in a cheaper way and used earlier in the design process. However, the lack of physical and sensory attributes, such as haptic and olfactory and the absence of the sensation of weight, limit the fidelity of representing human-product interactions [142].

Besides deciding whether to build a physical or computational prototype, designers need to determine whether to develop a low- or high-fidelity prototype. There are perplexing views in the literature regarding the appropriate level of fidelity [43, 110, 230]. For example, a study focusing on evaluating a lighting controller interface showed that a high-fidelity prototype reveals twice as many design problems compared to a low-fidelity prototype [110, 237]. High-fidelity prototyping provides richer sensory feedback and a higher level of interaction compared to low-fidelity prototypes. These attributes facilitate the identification of more design problems but at the expense of higher cost and development time [110]. In contrast, examples taken from numerous design studies show that low-fidelity prototypes are preferred over high-fidelity prototypes when modeling fundamental design attributes because the low-fidelity prototypes are easy, quick, and cheaper to build [46]. Some other studies claim that low-fidelity and high-fidelity prototypes are equally suitable in evaluating usability issues in interface design [227, 230].

In summary, there are various strategies to define a suitable prototyping medium to evaluate human-product interactions. One key take is that designers need to consider multi-faceted factors such as the type (physical or computational), fidelity level (high or low), interaction level (high or low), cost, and time spent on developing a prototype. Overall, as the number of factors increases, selecting the correct prototyping strategy, particularly for the design of human-centered products, becomes a perplexing query. The literature review shows that different studies offer contrasting results and views. Thus, there is a lack of comprehensive and widely accepted guidelines for designers to follow on building prototypes early in design [54].

4.3.2 Digital Human Modeling for Ergonomics

Digital human modeling (DHM) is a computational prototyping approach used for evaluating the ergonomics of products and workplaces. Commercially available DHM software has graphical representations of humans (manikins) with mathematics and science in the background [60,79]. DHM software can import computer-aided design (CAD) representations of products and workplaces to facilitate the prediction of injury and performance. There are several DHM software commercially available in the market such as RAMSIS [222], SANTOS [200], DELMIA [236], and JACK [42], which have interfaces that allow importing CAD models. Ergonomics analysis modules built within DHM software range from biomechanical analysis for manual material handling tasks to vision analysis for vehicle operations and time studies for assembly planning to energy expenditure and fatigue assessments for workers performance measurements [183]. Additional information about DHM software can be found in references [79] and [183].

The use of DHM as a design support tool within engineering design ranges broadly. Often it is used for assessing concept products to discover ergonomics issues. For example, Colombo et al. (2009) performed an ergonomic analysis of a family of three refrigerator products. It was reported that different users had different reaching and vision performances as they interact with the refrigerator. For instance, some areas on the fridge were accessible to 95^{th} percentile population, and some postures during maintenance did not conform with the National Institute for Occupational Safety and Health (NIOSH)'s lifting index, which increases the risk of injury [69]. In another example, DHM was used by the Ford Motor Company to find out the minimum clearance between potential drivers and the automobile interior panels. Designers performed a swept volume analysis to evaluate the minimum clearance for interior designs [232]. Likewise, DHM is also heavily used in the aviation industry, both military and civilian projects. For example, during the development of the F-15 fighter jet, DHM was used to assess whether a technician can reach and pull a heavy object during the installation of the radar equipment. Reach envelope and static strength analyses were performed to generate ergonomic reviews [126]. DHM is also used in healthcare [15], space research [107], sports [65], manual assembly [56], and consumer product development domains [82].

4.4 Methodology

In a previous study, different types of prototypes are explored to identify the suitable prototype to assess human performance during emergencies in a cockpit [25]. This study is a continuation of the methodology presented in that work [19]. This research focuses on identifying the appropriate level of fidelity for compu-

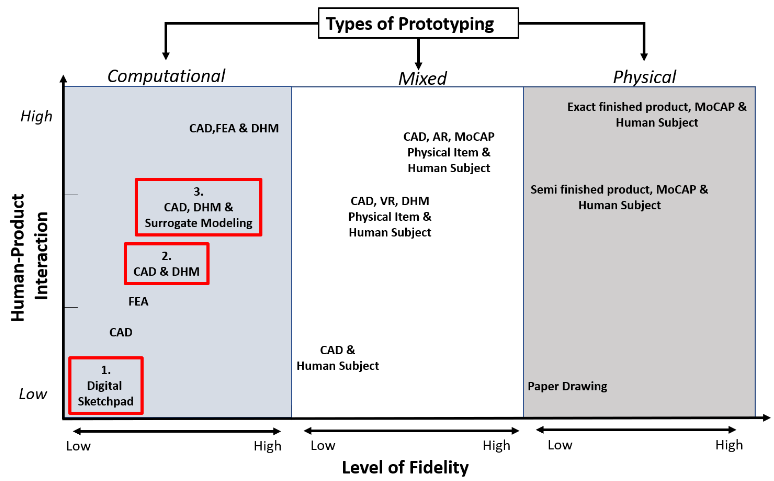

Figure 4.1: Prototyping methods for workplace or product design and human performance assessment - adapted from [25]

tational prototyping with varying degrees of human-product interactions. Figure 4.1 presents three computational prototyping methodologies with varying human-product interactions and fidelities, which are highlighted with rectangular boxes. Prototyping *Method #1*, a two-dimensional (2D) online sketching tool, has the lowest fidelity in terms of product visualization and ergonomics analysis capabilities. The integration of CAD and DHM represents the prototyping *Method #2*, which forms a digital prototyping environment that enables designers to perform quick ergonomic assessments based on three-dimensional (3D) CAD models and DHM ergonomics toolkits. Finally, the integration of CAD, DHM, and surrogate modeling is referred to as *Method #3*, which has the highest level of fidelity among the three methods described in this research due to its human performance and safety optimization capabilities. The prototyping methodologies are explored to understand how different fidelity levels with varying levels of human-product interactions affect the early design prototyping efforts. The following sections provide more details about each prototyping method.

4.4.1 Prototyping Method #1: Digital Sketchpad

Sketchpad 5.1 an online sketching tool [8] is chosen as a method to represent a low-fidelity prototyping methodology. Sketchpad 5.1 is a two-dimensional (2D) digital sketching pad where designers are given a blank canvas with drawing tools and stencils to conceptualize ideas via freehand style sketching. Unlike the DHM, Sketchpad 5.1 has no integrated anthropomorphic database to assist in creating the human form and no algorithms to assign postures. Instead, designers need to use anthropomorphic charts, ergonomics guidelines, or online databases to represent body-proportions as stick-figures. Further, designers can use stick-figures with geometry relations to perform quick-and-dirty ergonomic evaluations (e.g., 2D reach volume). However, even with anthropomorphic guidelines and geometric relationships, this prototyping method has the lowest fidelity in terms of its ability to mimic ergonomics of actual product use scenarios. The complexity of analyses highly depends on the expertise and human factors knowledge of the designer. Also, the 2D nature of the sketching interface adds to its limitations. Still, this method is used in early product development stages, especially during ideation and product conceptualization. It is significantly faster and less resource-intensive when compared to computationally expensive DHM models.

4.4.2 Prototyping Method #2: CAD and DHM

Prototyping *Method #2* uses CAD software to create product/workplace geometry and DHM to execute ergonomics analysis. In this study, the CAD file of the product is exported to Siemens JACK, [42] a DHM software, to conduct ergonomic evaluations. In terms of its ergonomics evaluation capabilities, this method has a higher fidelity than prototyping *Method #1.* DHM software includes anthropomorphic databases and inverse kinematic toolkits, which help designers to create manikins and assign realistic postures and motions. Also, various types of ergonomic analyses such as reach zones, vision obscuration, and lower-back compression assessments can be performed without conducting physical experiments. This method can be used to evaluate the ergonomics of products with low to intermediate complexity. However, if the aim is to design a product that has high-levels of human interactions, this method has some limitations. For example, one of the fundamental issues is that designers need to know the design variables that affect human performance beforehand. In the absence of this information, designers explore numerous configurations and investigate many options before reaching a consensus. Thus, this approach requires the exploration of the entire design space. Prototyping *Method #2* does not facilitate any computational tools for designers to explore the design space and determine the optimal human performance. With the absence of optimization methods, designers often rely on personal expertise and develop subjective assessments to explore potential design configurations. This approach often includes trial-and-error using a small batch of design configurations, which may not lead to an optimal solution. Usually, the heavy reliance on guesswork and the resulting subjectivity lead to inaccurate assumptions.

4.4.3 Prototyping Method #3: CAD, DHM and Surrogate Model

Prototyping *Method #3* uses surrogate models, in addition to CAD and DHM, to represent and explore the design space. The surrogate modeling is an approximation method that is used for evaluating design objectives and constraint functions when real models are not available. This approach has been used in many engineering studies as a computationally cheaper methodology to explore design spaces when an outcome of interest cannot be directly measured [17, 18, 34, 106, 125, 155]. The surrogate modeling technique presented in *Method #3* is adapted from a previous study of Ahmed et al. (2018) [16]. The study uses a Kriging modeling technique to enable designers to tie human performance to the design variables by systematically assessing human performance for a large number of design configurations. In the surrogate modeling approach, designers first change one design variable at a time to observe the variation in human performance outcomes and use statistics to identify the design variables that significantly affect human performance. Once the design variables are identified, the Latin Hypercube Sampling (LHS) method [164] is used to generate sample design configurations. Next, human performance data for each design configuration is extracted using DHM to create a Kriging surrogate model [125]. The surrogate model is then explored to find the design configuration that gives optimal human performance. Since the surrogate modeling approach has a higher fidelity when compared to prototyping *Methods #1* and *#2*, it reduces the designer's subjectivity by enabling a more systematic design space exploration.

4.5 Case Study

In this paper, three computational prototyping methodologies with different fidelity levels (low-, medium-, and high-fidelity) are compared to study their adequacy for evaluating ergonomics of products that comprise low- to high-levels of human-product interactions. *Method #1*, *Method #2*, and *Method #3* are used as prototyping strategies to perform computational ergonomics analyses on a generic wall-mounted Cabinet, an Automobile Steering Wheel, an Assembly Line, and a simplified Cockpit model. These case studies contain varying levels (low- and high-levels) of human-product interactions, which require different types of ergonomic analyses, as shown in Fig. 4.2. Design variables, design objectives, and types of ergonomic assessments are listed at the bottom of Fig. 4.2 for each case study. The level of human-product interaction increases from left to right (from Cabinet to Cockpit #2), which is also evident by the increase in the number of variables and objectives. The vertical axis, which ranges from low to high, represents prototyping fidelity levels. Prototyping *Method #1* has the lowest fidelity among the three as it only has a sketching tool without any embedded ergonomic analysis capability, as shown in Fig. 4.2. Prototyping *Method #2* has higher fidelity than *Method #1* because, in this approach, CAD is used to represent the workplace, and

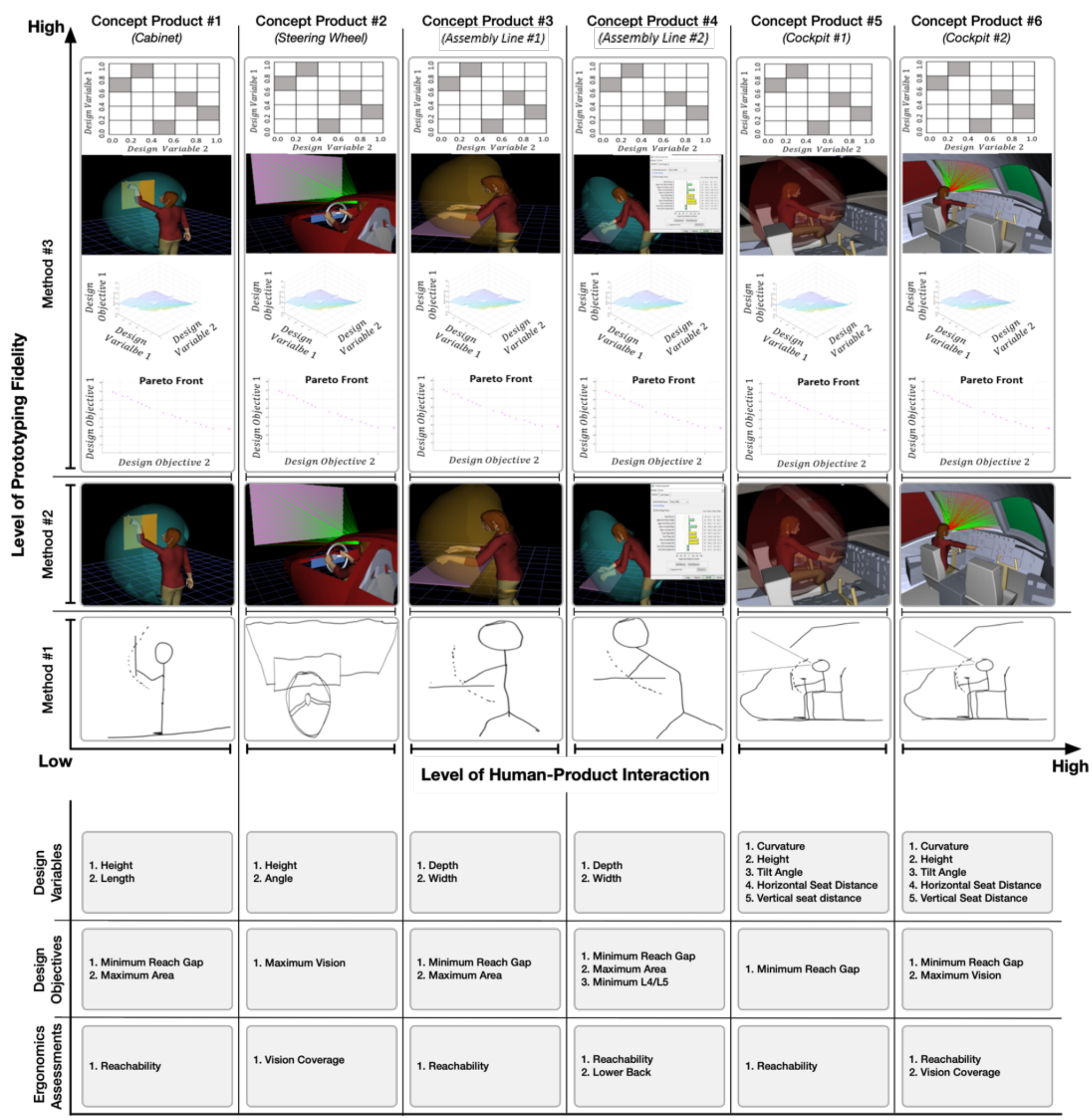

Figure 4.2: Ergonomic assessment of the products used in this study with prototyping *Method #1*, *Method #2* and *Method #3*

DHM is used for performing ergonomic analysis, as shown in Fig. 4.2. Prototyping *Method #3* has the highest fidelity among the three because not only it uses CAD and DHM, but, additionally, it implements surrogate modeling and optimization to explore larger design space and generate a larger solution space. Prototyping *Method #3* uses the Latin Hypercube Sampling (LHS) method to generate multiple configurations of the workplace, as shown in the top row of the *Method #3* in Fig. 4.2. The ergonomic analysis for each configuration is performed, and the generated data is used to create the surrogate model, as shown in the second and third-row, respectively. Finally, optimization is used to explore the design space and find the design configuration where the human performance is maximum, as shown in the fourth row. Compared to *Method #2*, these additional steps of LHS, surrogate modeling, and optimization in *Method #3*, reduces the designer bias when generating workplace configurations and design space exploration; thus, increases the fidelity. Note that the illustrations for LHS in Fig. 4.2, shown in the *Method #3* row on the y-axis, represents generic surrogate modeling models, not specific optimization results for each study.

In this study, a 5^{th} percentile Japanese female anthropometry is considered as the computational manikin model to represent the near-smallest population percentile in ergonomic assessments. It is because many conventional consumer products and workplace designs focus on the *"average"* users and ignore the population extremities. Often, a majority of the ergonomics issues regarding accessibility are associated with users from anthropometric population extremities. The design objectives and variables used in the study are provided in Fig. 4.2. The ranges (e.g., maximum and minimum reach envelop measures for the manikin) of the design variables are gathered according to the anthropometric extremities of the manikins used in this study and the consumer databases corresponding to the products [105].

4.5.1 Low-Level Interaction: Cabinet

In this study, the Cabinet model represents a generic product that has low-level human-product interaction. The scenario considered is someone trying to reach a specific point in the cabinet. Ideally, a cabinet needs to be designed with sufficient space so that it can hold as many items as possible, and at the same time, allows users ease of access. The cabinet geometry represents a simple form factor (Fig. 4.3 - CAD model). The height and length are the design variables, and reachability is the only ergonomic factor affecting human interaction. As a result, the cabinet has a simple design space with low-level human-product interactions, which requires a relatively simple ergonomic assessment. Thus, in this study, the first objective is to increase reachability. It involves minimizing the reach gap between the manikin's index fingertip and the cabinet corners, enabling the manikin to access all four inner corners of the cabinet. And the second objective is to maximize the cabinet area.

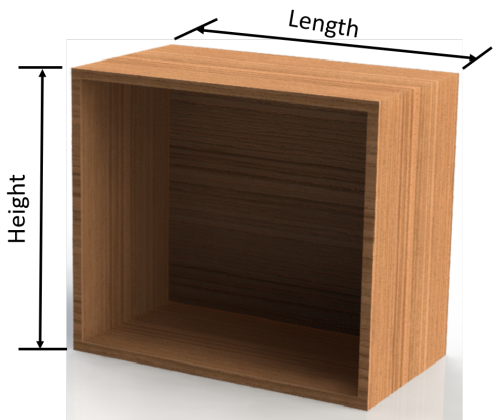

Figure 4.3: A CAD model representing a wall mounted cabinet

4.5.2 Low-Level Interaction: Automobile Steering Wheel

This case study's design objective is to provide maximum vision coverage (forward binocular vision) to the driver since the steering wheel location can affect the visibility of the dashboard and road elements (e.g., road signs, pedestrians, other vehicles) which negatively affect the driver's performance by increasing obscuration zones. Design variables of interest are the vertical position and tilt angle of the steering wheel. This scenario presents a low-level human-product interaction example, as there is only one design objective (maximum vision coverage) and two design variables (vertical position and tilt angle) to consider. The ergonomic assessment required for this study is vision coverage.

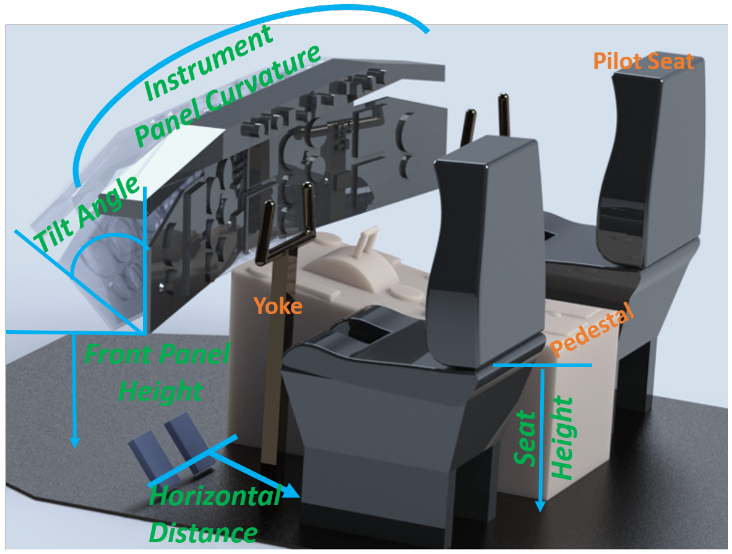

Figure 4.4: A simplified CAD modeling representing Boeing 767 cockpit

4.5.3 Low to Mid-Level Interaction: Assembly Line #1 and #2

Assembly Line #1 has similar ergonomics requirements and interaction levels as the cabinet study. The manikin is expected to reach each corner of the Assembly Line without bending. The design objective is to minimize the reach gap and maximize the surface area. Assembly Line #2, on the other hand, has a different level of human-product interaction when compared to Assembly Line #1. Thus, the study requires additional ergonomic assessments. In the Assembly Line #2 scenario, the manikin is allowed to bend forward while reaching the corners of the Assembly Line. Therefore, the manikins' L4/L5 (compression force measurements between 4^{th} and 5^{th} lumbar sections) need to be evaluated for ergonomic adequacy. As a result, the design objectives are increased from two to three, with the addition of the L4/L5 measurements.

4.5.4 High-Level Interaction: Boeing Cockpit #1 and #2

The aviation sector uses HFE guidelines heavily to evaluate pilot and crew performance. Within a cockpit environment, pilots interact with several objects such as instrument panels, yoke, pedestal, displays, and controls. Also, pilots need to have unobscured visual detection through the windshield, especially during take-off and landing. Two cockpit models are used to represent high-level human interaction scenarios. Although both studies share the same cockpit environment and have the same number of design variables (Fig. 4.4), there are different types of ergonomic assessments executed. For the Cockpit #1 case study, only the pilot's reach task is assessed, whereas, in Cockpit #2, both reach and vision tasks are evaluated. Hence, in Cockpit #1, the objective is to minimize the reach gap, whereas, in Cockpit #2, the aim is to reduce the reach gap while maximizing the vision coverage.

4.6 Results

Six concept models were developed using the three computational prototyping methodologies (*Method #1, #2, and #3*). The relevant ergonomic assessments (Fig.4.2) were performed on each prototype to explore whether the differences in fidelity and the human-product interaction levels have any effects on the quality

Table 4.1: Design objective results using three prototyping methods (Method #1, #2, and #3)

		Cabinet	Steering Wheel	Assembly Line #1	Assembly Line #2		Cockpit #1	Cockpit #2	
Prototyping Methods	Solution Points	Reach Gap (cm)	Vision (%)	Reach Gap (cm)	Reach Gap (cm)	L4/L5 (N)	Reach Gap (cm)	Reach Gap (cm)	Vision (%)
Method # 1 (Sketchpad)	1	0	N/A	0	N/A	N/A	N/A	N/A	N/A
	2	0	N/A	0	N/A	N/A	N/A	N/A	N/A
	3	0	N/A	0	N/A	N/A	N/A	N/A	N/A
Method # 2 (CAD and DHM)	1	0	72.23	0	1.61	950.74	0	5.73	34.51
	2	0	73.45	0	2.83	1028.36	0	4.35	34.82
	3	0	71.66	0	3.43	1023.59	0	4.63	36.17
Method # 3 (CAD, DHM and Surrogate Modeling)	1	0	84.71	0	0.55	820.45	0	3.26	37.86
	2	0	85.74	0	0.83	953.22	0	3.12	37.33
	3	0	76.04	0	0	869.21	0	1.76	38.16

of the ergonomics outcomes. The results are discussed in this section.

4.6.1 Prototyping Method #1: Sketchpad

Figure 4.2 shows the sketches representing a 5^{th} percentile Japanese female interacting with all six products. The manikin sketch in *Method #1* does not accurately represent population percentiles (e.g., 5^{th} percentile Japanese female in this case), since the sketchpad tool does not contain any integrated anthropometric data. Therefore, each manikin had to be sketched manually based on the Japanese 2006 anthropometric database as stick figures. The length of a 5^{th} percentile Japanese female arm, from acromioclavicular joint (joint at the top of the shoulder) to index fingertip, was found to be around 62.53 cm. This information is used to manually sketch a circle with an approximate radius of 62.53 cm to illustrate a representative reach envelope (2D semi-circle). It should be noted that only the reach assessment can be evaluated using this approach. Ergonomic assessments of the vision coverage and L4/L5 analysis can not be executed using a 2D sketchpad, which is a limitation of the *Method #1*.

The wall-mounted cabinet, as shown in Fig. 4.2 was kept at a constant shoulder height of 121.61 cm above the ground and 15 cm away from the manikin. Since the cabinet dimensions are symmetrical and the left arm was solely used during the reaching task, only one-half of the cabinet was utilized during the ergonomics assessment. The reach envelope, as shown in Fig. 4.2, was assumed to be a sphere. The geometrical relations, such as the largest rectangle that can be inscribed in a circle, were used to explore the cabinet's length and height. Since a square has the largest area inside a circle, the length and height of the cabinet are found to be around 44.21 cm on each side, resulting in a cabinet configuration that has the largest area within the reach envelope. The results of the reach assessment were shown in Table 4.1.

The sketchpad tool in *Method #1* was successfully used to assess the reach envelope for products with a low number of design variables and objectives, (See Table 4.1). However, when the number of design variables are high, *Method #1* is not capable of replicating ergonomics assessments for reach envelope analysis. For example, the Cockpit #1 study has only one ergonomics design objective (reach envelope) similar to the Cabinet case study. However, the ergonomics evaluation cannot be performed for Cockpit #1 via the sketchpad because there are five design variables, making it infeasible to represent within a 2D space. Likewise, it wasn't possible to assess the obscuration zones as well as the lower-back analysis using the Sketchpad approach.

4.6.2 Prototyping Method # 2: CAD and DHM

A CAD file for each product was created and exported into DHM software (Siemens JACK) for running ergonomic assessments. Unlike prototyping *Method #1*, the *Method #2* can assess more complex ergonomics analyses that require 3D posture evaluation and interaction with the CAD environment, such as L4/L5, vision coverage, and reach assessment. A 5^{th} percentile Japanese female manikin was created to perform a reach assessment for the Cabinet, Assembly Line, and Cockpit case studies. A reach envelope that has the shape of a bubble/sphere was generated in JACK by tracing the tip of the left-arm index finger of the manikin (Fig. 4.2). The translucent bubble represents the volume in which the manikin has extended reach when using the left arm. In the next step, various configurations of the Cabinet, Assembly Line, and Cockpit models were created by changing design variables. Each configuration includes the points of interest that were within the reach envelope. This approach ensures that the manikin has the reach coverage for all points of interest for each product. The results are presented in Table 4.1. For instance, the length and height of the cabinet were found to be around 45 cm. The process was iterated multiple times to achieve better consistency.

For the Steering Wheel study, the design objective was to maximize the drivers' vision of the dashboard and windshield. The binocular vision coverage assessment tool of JACK was used to evaluate the vision coverage. The design variables were the height and angle of the steering wheel. As the steering wheel was manually moved up and down and tilted, the optimal vision coverage percentage values were measured, as shown in Table 4.1. The L4/L5 analysis for the Assembly Line #2 case study was performed using a similar approach, where the design variables were manually adjusted to find a configuration with the minimum L4/L5 forces.

It should be noted that the Cabinet, Steering Wheel, Assembly Line #1, and Cockpit #1 case studies require only one ergonomic assessment, whereas the Assembly Line #2 and Cockpit #2 require multiple ergonomic assessments. When only one ergonomic evaluation is desired, designers can focus solely on that ergonomic assessment and find the optimal design solution without running exhaustive design space exploration. However, when multiple ergonomic assessments are present, designers need to carefully configure the design variables and search the design space such that human performance is optimal for all ergonomic measures that are under evaluation.

In the Cockpit #2 study, the design objectives were to minimize the reach gap and maximize the vision coverage. Figure 4.2 shows the reach and vision coverage assessments for a 5^{th} percentile Japanese female manikin placed inside the cockpit model. The values of the five design variables are changed according to the designer's subjective choice when creating new cockpit configurations, which were then evaluated for instrument panel reach and vision coverage assessment. Reach assessment was calculated by measuring the reach gap between the left-hand index finger of the manikin and the surface of the instrument panel. Vision analysis was performed by calculating the percentage of the visible area of the windshields. In Figure 4.2, the green rays show the visible region, and red rays show the obscured region. It should be noted that identifying the optimal configuration that results

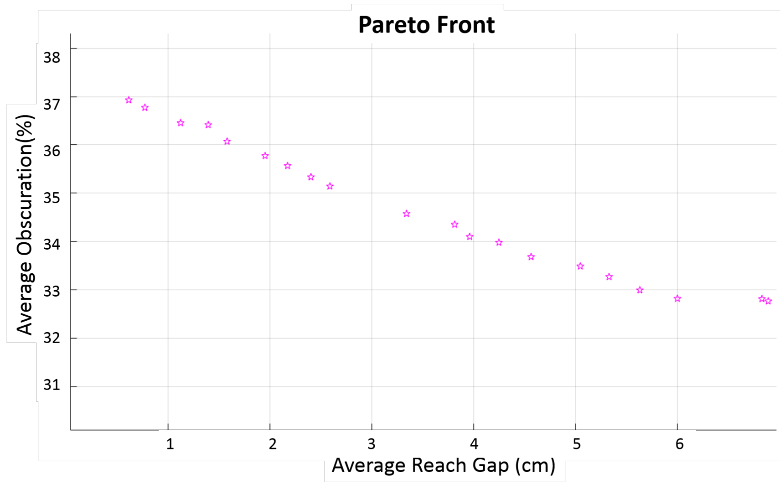

Figure 4.5: Pareto Analysis of the design objectives of Boeing 767 Cockpit design

in minimum reach gap and maximum vision coverage it is up to the designer's expertise and knowledge and may take multiple iterations. These back-and-forth iterations are repeated many times until the designer is satisfied with the design solution. The reach gap and vision coverage results are shown in Table 4.1.

4.6.3 Prototyping Method #3: CAD, DHM and Surrogate

As mentioned in Section 3.3, *Method #3* applies surrogate modeling along with CAD and DHM [16,23]. Therefore, *Method #3* shares the same prototyping environment as *Method #2* with the addition of surrogate model based optimization study (See Fig. 4.2). Although *Method #2* and *Method #3* have identical ergonomics assessments (reach gap, L4/L5, and vision coverage), the approach for creating new product configurations is different. In prototyping *Method #3*, product configurations are created using Latin Hypercube Sampling (LHS), which eliminates the subjectivity in creating new configurations as observed in prototyping *Method #2*. LHS enables designers to generate configurations that cover a broad spectrum of design variables, representing a larger design space. Furthermore, by running optimization using the surrogate model, the best product or workplace configurations that can lead to optimal human performance can be identified.

For prototyping *Method #3*, the design objectives are to create products that have a minimum reach the gap, minimum L4/L5, and maximum vision coverage. For example, for the cabinet, a square shape with a 45.6 cm length is found to have the largest coverage area with a minimum reach gap. Unlike the cabinet, the Assembly Line and cockpit case studies have multiple design objectives that are contradictory to each other. Pareto Fronts are built for those products that have conflicting design objectives. Pareto Fronts help in visualizing the trade-offs between the two design objectives and selecting design configurations based on the design objective priorities. For example, the Pareto Front of the Cockpit #2 case study is shown in Fig. 4.5, where one design objective gets better while the other gets worse.

To improve consistency, the optimization of the surrogate model is iterated multiple times. The results of the ergonomic assessments performed using this approach are available in Table 4.1. Overall, Table 4.1 summarizes the results of the ergonomic assessments performed using each prototyping method (*Method #1, #2 and #3*). Note that the cockpit model could not be designed accurately using the sketchpad, so no result is shown in Table 4.1. The results of the cockpit model using prototyping *Methods #2 and #3* are analyzed further. An independent two-sample t-test is used to identify whether designing the cockpit using different prototype fidelity yields any differences in human performance. The t-test results are shown in Table 4.1. The p-values indicate that the results obtained from the two prototyping strategies are significantly different from each other.

Table 4.2: Statistical analysis of the product design results obtained using prototyping Method #2 and Method #3

		Steering Wheel	Assembly Line #2		Cockpit #2	
		Vision (%)	Reach Gap (cm)	L4/L5 (N)	Reach Gap (cm)	L4/L5 (N)
Mean	Method #2	73.98	1.87	999.98	4.87	35.13
	Method #3	83.18	0.39	869.66	2.67	37.73
Standard Deviation	Method #2	2.82	1.24	82.26	0.734	0.85
	Method #3	4.06	0.36	54.90	0.84	0.40
p-value		0.004	0.054	0.022	0.028	0.019
95% CI		3.98 to 14.41	-2.99 to 0.04	23.49 to 25.65	0.39 to 4.00	0.82 to 4.38

4.7 Discussion

This research aims to study the intricacies between the fidelity level, human-product interaction level, and ergonomic assessment and how it can be adopted in the Industry 4.0 paradigm to enable computational prototyping to be part of the product development. Successful human-centered prototyping strategies can help in mass customization by minimizing the product development cost and time. Hence, in this paper, we study the level of fidelity needed in computational prototypes when performing different types of ergonomic assessments on products with varying levels of human-product interactions. Six concept products with different ergonomic assessment requirements (reach, vision, and L4/L5) and different levels of human-product interactions (low, mid, and high) are prototyped using: (1) Prototyping *Method #1* (low-fidelity): digital sketchpad, (2) Prototyping *Method #2* (mid-fidelity): CAD and DHM, and (3) Prototyping *Method #3* (high-fidelity): CAD, DHM, and Surrogate Modeling. The results and statistical analysis are presented in Table 4.1 and Table 4.1. Several noteworthy prototyping findings extracted from this study are summarized in the following paragraphs.

Table 4.1 shows that the low-fidelity prototyping tool is suitable for evaluating ergonomics for the Cabinet and Assembly Line #1 case studies. One can see that the reach assessment can be performed with the low-fidelity sketchpad since it involves only simple geometry calculations. As seen in Table 4.1, the reach gap measurements for the Cabinet and Assembly Line #1 were found to be zero, using all three prototyping methods. Thus, all three methods are suitable for performing the reach assessment for products that contain low- to mid-level human interactions. On the other hand, prototyping *Method #1* was not useful when assessing the reach in the Cockpit #1 scenario. Even though the Cockpit #1 model only required just the reach assessment, performing reach analysis with a 2D sketchpad was infeasible. Five design variables in total and a high-level of human interaction make the low-fidelity prototyping tool sketchpad not suitable for this case study. Thus, one can see that *Method #1* is not an appropriate approach to deliver the reach assessments for products that contain high levels of human interaction. When a design problem includes a high-level human-product interaction and 3D configurations, using a low-fidelity computational prototyping method, as seen in *Method #1*, is not recommended.

Results in Table 4.1 show that the mid-and high-fidelity level prototyping methods were suitable for prototyping all six concept products. The question here is whether the difference in fidelity levels affect the design solutions. The answer lies in the results of the independent two-sample t-test in Table 4.1. A random sample is selected and the normal distribution of the data is checked before the t-test is carried out. All p-values are significant ($p < 0.05$) except for Reach Gap in Assembly Line #2, meaning that there was a difference in the ergonomic assessment results between the prototyping strategies. The difference in the design solutions can be attributed to the fidelity level of the prototype. As mentioned before, designers use their expertise when working with prototyping *Method #2*, which often leads to an under-exploration of the design space. Whereas, in prototyping with *Method #3*, a surrogate model is built to find optimal design space using optimization techniques. Prototyping *Method #3* eliminates a majority of the subjectivity and aid designers in exploring the design space systematically to find better solutions as compared to prototyping *Method #2*. The differences between the capability of prototyping *Method #2* and prototyping *Method #3* become more apparent as the design space or human-product interaction increases. For example, the p-value for the Reach Gap of Assembly Line #2 is close to 0.05, (i.e., the mean value obtained from prototyping *Method #2* and prototyping *Method #3* is not different.) This indicates that the design space related to the reach gap assessment is small when there is a low-level interaction or only two design variables to consider.

Additionally, it is also observed that *Method #2 and #3* produce contrasting outcomes when both design objectives are equally prioritized. One can see that combined mean differences are higher and p-values are lower. It is because, in prototyping *Method #2*, designers only manipulate the design variables in a limited number of ways to create the cockpit design configurations, which can achieve both design objectives equally. However, in prototyping *Method #3*, these limitations are eliminated with the use of the surrogate model and optimization tool.

Table 4.1 shows that all three prototypes are suitable for prototyping products that include the reach assessment and low-level human-product interactions. Moreover, Table 4.1 presents that higher fidelity prototypes are better in prototyping products that possess higher levels of human-product interactions. This raises a question: if all levels of fidelity are appropriate to use for product design, then what level of fidelity should one choose? To address this question, one needs to consider other factors, such as the cost of resources that go into building a prototype. Using the cabinet scenario as an example, prototyping using a sketchpad takes around three to five minutes, finding the approximate anthropometry data and dimensions take another three to five minutes. Finally, the calculations take around another minute or two. Therefore, prototyping using a sketchpad option takes approximately ten minutes. In contrast, prototyping *Method #2* takes about fifteen to twenty minutes as the designer needs to create various CAD files and test ergonomics using DHM software. The prototyping *Method #3* takes the longest time of approximately an hour. Prototyping *Method #3* requires creating configurations of design variables, creating a surrogate model, and using an optimization tool to explore the design space. Also, prototyping *Method #2 and #3* are costlier than prototyping *Method #1* due to the software expenses and time commitments (e.g., JACK, SolidWorks, and MATLAB). As the level of fidelity increases (from

Method # 1 to # 3), the cost of resources in terms of time and money also increases; however, the cabinet configurations and ergonomic assessment yield results that are close to each other. Hence, a low-fidelity computational prototype can be suitable to design a product or workplace with low-level human interactions and a limited design configurations (small design space).

To sum up, one can conclude that the low-fidelity prototyping approach (prototyping via a 2D sketchpad tool) is limited in products with high human-product interactions. Also, low-fidelity prototyping has limitations in performing complex ergonomic assessments, for example, for the vision and L4/L5 analyses. Yet, the low-fidelity prototyping approach can still be used in executing ergonomics studies in scenarios that include low-level human-product interactions. If the human-product interaction level is not high then low-fidelity prototyping produces outcomes comparable to mid-and high-level fidelity prototypes while using fewer resources. Mid- and high-level fidelity prototypes are recommended when high-level human-product interactions are available, and when designers are interested in applying a wide range of ergonomic assessments. However, as the level of human-product interaction increases, the difference in the accuracy between the mid-fidelity and high-fidelity prototype results becomes more prominent. A high-fidelity prototype produces more accurate results than a mid-level prototype because it enables designers to do a more thorough and objective design space search. Overall, it can be suggested that designers must decide which fidelity level prototype to use after doing a trade-off study between the accuracy of the ergonomics outcomes and the available resources.

4.8 Conclusion and Future Work

Although the Industry 4.0 concept promises better control of the overall product development process, there is a lack of computational frameworks that can inject ergonomics and human-factors engineering early in design. This shortage is particularly crucial for prototyping human-centered products where the stakes are high. Ergonomically inferior products are associated with reduced quality, lousy safety records, and low-levels of user satisfaction. Overall, they accumulate an extensive cost to manufacturers in the long run due to product recalls, loss in market share, and diminished customer loyalty. Thus, a smooth transformation within the Industry 4.0 paradigm cannot occur without bringing computational ergonomics tools and methodologies into the loop, specifically to address the needs in the digitized prototyping process. In this study, a unique computational ergonomics approach is demonstrated to solve some of the above shortcomings.

One of the limitations of this study is that it only focused on computational prototyping approaches. The prototyping findings may apply to other types of prototypes, such as physical and mixed prototypes, but require further studies for validation. Also, the results presented in this research are generated through computational models and not validated within an actual product development practice. The results can be validated by replacing the computational prototypes with low-, mid-and high-fidelity physical prototypes and substituting digital manikins with the actual users for human subject ergonomics data collection. Another limitation of this study is that only three types of ergonomic assessments (reach, vision, and L4/L5) are considered, making the results only valid for a limited scope of ergonomics evaluations.

One avenue of future work is to develop a computational prototyping framework that integrates prototyping best practices with ergonomics and human factor guidelines to guide designers and engineers to prototype human-centered products. Currently, no prototyping framework considers ergonomics and human factors guidelines concurrently. However, the current research findings related to prototyping that considers ergonomics are inadequate. Hence, to develop the prototyping framework for a human-centered product, research studies related to other ergonomics assessments such as fatigue, strength analysis, comfort analysis, and cognitive analysis need to be performed initially. We expect these research studies to provide design guidelines and best practices regarding human-centered prototyping activities, leading to the creation of more comprehensive computational prototyping frameworks to support Industry 4.0 objectives. Further, the computational human-centered product prototyping framework can be integrated with a Graphical User Interface (GUI) or with next-generation Computer-Aided Engineering (CAE) tools to automate the prototyping process and generate conceptual prototyping strategies. The automation and digitization of the prototyping process would fit into the overarching goal of Industry 4.0. of achieving higher efficiency and productivity.

Chapter 5: A Pre-Prototyping Framework to Explore Human-Centered Prototyping Strategies During Early Design

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5.1 Abstract

Current prototyping frameworks are often prompt-based and heavily rely on designers' experience. The lack of systematic guidelines in prototyping activities causes unwanted variation in the quality of the prototype. Notably, there is limited or no prototyping framework that enables human factors engineering (HFE) guidelines to be part of the early product development process. This paper proposes a Pre-Prototyping framework to render human-centered design strategies to guide designers before the hands-on prototyping activity starts. The methodology consists of extracting key factors related to prototyping and human factors engineering principles based on an extensive literature review. The key elements are then combined to form the prototyping categories, dimensions (theory), and tools (practice). The resulting prototyping framework focuses on developing prototyping strategies consisting of theoretical guidelines and practical tools needed during the prototyping of human-centered products. The framework provides systematic guidance to novices in ergonomics and human factors design during the early stages of the design process to have a head start in building the prototypes in the right direction. A case study is presented to demonstrate a walk-through of the proposed Pre-Prototyping framework. A validation study is performed with an Intervention and a Control group to evaluate the efficacy of the proposed Pre-Prototyping framework. It is found that the prototyping strategies created by the Intervention group using the proposed framework have a higher average prototyping score than that of the Control group that created the prototyping strategies

only based on experience and intuition.

Keywords: Design, Prototyping, Human-Centered Design, Human Factor Engineering, Digital Human Modeling

5.2 Introduction

Although numerous interpretations exist within different domains, prototyping is a critical step in the product development process and involves numerous activities that are known to be very resource-intensive [231]. Pham and Gault (1998) define prototyping as *"An essential part of the product development and manufacturing cycle required for assessing the form, fit, and functionality of a design before significant investment in tooling is made"* [182]. Camburn (2015) et al. describes *"Prototyping is the systematic development and testing of a new product design concept to establish its feasibility and enhance detail design of pre-production models"* [54]. The research and development (R&D) department of the top 20 companies spent around 142 billion dollars to innovate new products, and 40 to 46% of these products did not even make it to the market [66]. For example, Dyson Ltd., a British design company that manufactures household appliances, went through over 5000 prototypes and took five years to come up with the revolutionary cyclonic vacuum [129].

Even though prototyping is a fundamental activity within product development, the prototyping process is generally ad-hoc and depends heavily on the experience and creativity of designers [54]. Currently, there is no prototyping framework exist that is comprehensive, widely accepted, and is easy to implement [54, 66, 144, 166]. Existing prototyping frameworks often focus on prompt-based and hands-on activities rather than providing theoretical and practical guidelines on how to create prototypes [66, 144, 166]. The lack of systematic guidelines can cause variation in prototyping quality even when designers follow similar prototyping strategies [166].

Another shortcoming common to current prototyping frameworks is the lack of ergonomics integration or sparse consideration of human factor engineering (HFE) guidelines. HFE is a multi-discipline domain that concerns the theory and practice of ergonomics to optimize human well-being and overall system performance [103, 134]. HFE aims to reduce human error, increase productivity, and enhance safety and comfort by applying theory and practice from a wide range of disciplines to design and evaluate products, services, tasks, processes, environments, and systems [239]. Although HFE is theoretically positioned as one of the most crucial components of the product development process, it is often not built in the early stages of prototyping and many times incorporated at the later part of the design process [79,90,140]. The absence of HFE in prototyping causes products not to meet the ergonomics, safety, and usability-related standards. A last-minute effort of integrating HFE design principles or taking corrective measures on functional prototypes (or while products are in use) is regarded as reactive ergonomics approach [94, 118], which is usually associated with additional costs and time on the product development [246].

One of the roadblocks in integrating HFE early in the design process is the lack of human-product interaction data [95]. This data can often be collected by creating prototypes; however, there is no comprehensive prototyping framework that guides designers on building a prototype to collect human-product interaction data. Prototypes can be either physical, computational, or mixed, with each type has its own merits and demerits. Similarly, prototyping has other factors such as fidelity, iterations, and complexity that need to be considered before creating a prototype. On the other hand, in terms of measuring human performance, the type of ergonomic assessment, level of human-product interactions, and performance shaping factors (PSFs) need to be taken into account before collecting the human-product interaction data. Currently, no prototyping framework combines the prototyping guidelines along with HFE design principles to provide prototyping strategies for human-centered product development activities. Hence, to address the gap, the following overarching research question is formulated: *What prototyping framework should be used to design and assess human-centered products?* The Pre-Prototyping framework proposed in this research focuses on the design and analysis of human-centered products and workplaces by integrating prototyping theories and technologies with HFE principles. The prototyping strategies consist of design decisions that dictate what theoretical approaches and technology tools need to be considered before the actual prototyping activities start.

5.3 Step 1: Literature Review

A concise literature review on prototyping guidelines, existing frameworks, HFE, human-product interactions, and ergonomic assessments are provided in this paper. Although a detailed literature review is not exclusively presented due to space limitations, most of the relevant literature and a summary of critical findings are presented in Section 2 and Section 3, respectively.

5.3.1 Prototyping Framework

A prototyping framework that is comprehensive and widely accepted in the scientific community is scarce [54,66,166]. Christie et al. (2012) developed nine factors and thirteen questions that can assist in making engineering decisions while building prototypes [66]. It was hypothesized that using this method, engineers can create prototypes strategically to have better project efficiency and success rate. Camburn (2015) et al. proposed a prototyping strategy to enhance the outcome of the prototyping efforts. The methodology consists of identifying prototyping best practices and synthesizing heuristics from prototyping literature. A prototyping guideline in the form of a survey tool was developed from these heuristics. The prototyping strategy is then validated by experimental investigation, and it was found that the proposed strategy improves design outcomes [54]. Menold (2017) et al. proposed a prototyping framework called Prototyping for X (PFX), which hypothesized four specifications that any prototyping framework should meet. Further, three primary functions of the prototype were identified. Additionally, three lenses (feasibility, viability, and desirability) were proposed to integrate human-centered design methods. The proposed prototyping framework was evaluated, and it was found that the PFX team produced higher-quality prototypes than the non-PFX team [166]. Lauff (2019) et al. proposed a prototyping canvas that can help designers create purposeful prototypes. It was noted that the current prototyping best practices are challenging to implement in practice as they lack simplicity and effectiveness [144]. The proposed prototyping canvas was based on three prototyping principles, "Purpose, Resources, and Strategy", and the layout was inspired by the Business Model Canvas, a strategic management template for developing new business models.

As mentioned earlier in the paper, no comprehensive and widely accepted prototyping framework is available for designers, mainly for early design activities. The prototyping frameworks reviewed in this section do not consider human-centered design practices at the core. For example, the prototyping strategy proposed by Camburn (2015) et al. is oriented toward product design in the electromechanical domain. Although Menold (2017) et al. attempted to address the user-centered design practices, their framework did not incorporate guidelines from HFE principles. In general, the HFE guidelines and prototyping findings from ergonomics and usability literature were missing. Another shortcoming of the above prototyping frameworks is that they only provide prototyping prompts rather than bringing prototyping guidelines from the best practices found in the literature. These frameworks do not include the necessary *"know-how"* or the tools to create a prototype. The recommendation for prototyping tools is valuable, particularly among novice engineers, since the concept and quality of prototyping differ vastly due to the lack of experience [74, 166]. This finding is also evident in the works of Camburn (2015) et al. and Menold (2017) et al., where the different teams created prototypes of various quality even though they all used the same prototyping strategy and framework [54, 166]. The variation in prototype quality among the same experimental group emerged because each group was given only prototyping prompts and ques. Therefore, the framework relied heavily on participants' experience and intuition. In addition to these shortcomings, Lauff (2019) et al. mentioned that the current prototyping frameworks lack clarity and cannot be effectively used in practice [144].

5.3.2 Prototyping Human-Centered Design

Demirel and Duffy (2013) define human-centered design (HCD) as a design approach which *" integrates different technical and social fields of expertise to enhance the well-being of people by improving product-user interaction, increasing usability, safety, and efficiency"* [80]. HCD includes methods such as communication, interaction, and simulation to facilitate human and product interaction. The HCD approach also aims to improve the product characteristics or engineering specifications based on customer requirements or, in other words, based on needs, abilities, and limitations of users [82, 137]. The definition of HCD is similar to HFE; however, HCD is not a scientific domain, but a design approach [80].

In traditional human-centered product development activities, a physical prototype is mostly used for ergonomic assessment, and the design modifications usually occur at the later stages of the design process [39, 165]. However, with the advancement of computer-based modeling and simulation technologies such as digital human modeling (DHM) and mixed prototyping via virtual and augmented reality (VR and AR), a physical prototype is substituted with a computational and mixed prototype when it is feasible [22, 33, 58, 89, 147, 214]. DHM is defined as *"...the digital representation of humans inserted in a simulation or virtual environment to facilitate the prediction of performance and safety of a worker"* [79]. DHM approach can be used to perform various ergonomic assessments such as reach, vision, fit, and energy expenditure. Although DHM is suitable for design studies that focus on physical ergonomic assessments, it has limited fidelity and lacks cognitive analysis tools [60, 143, 214].

On the other hand, mixed prototyping is defined as *"An integrated and co-located mix of physical and virtual components usually seen using a see-through head-mounted display (HMD)"* [44]. In mixed prototyping, via VR or AR, the human subject can be immersed in the product or workplace using visual, audio, tactile, and functional realism [44, 175]. Designers can use mixed prototyping to see how the users interact with the product or workplace without building the actual physical product or only partially building a subset of the physical product [24, 33]. However, a mixed prototype has limited haptic feedback, which reduces the tactile realism [36, 149]. This limitation can be partially circumvented by creating physical objects to enhance tactile feedback; however, the amount of mixing between physical and virtual objects is not specified in the literature.

Duffy (2007) mentioned that the level of human-product interaction can indicate the balance between physical and virtual objects used in a prototype. It was proposed that for low-level human-product interaction, a full computational (virtual) prototype is preferable, and for high-level interaction full physical prototype is preferable [88]. Another factor that plays a role in determining the type of prototype (i.e., physical, computational, or mixed) that can be used for ergonomic assessment is the type or nature of the ergonomic factor itself. Karwowski has listed around hundred ergonomic subfactors that are classified under the major six ergonomic factors in Table 7, Chapter 1 in the Handbook of Human Factors and Ergonomics [199]. The prototyping literature provides no specific guidelines about how to build prototypes that can be used to evaluate human-product interaction for any particular ergonomic factor. Since the prototyping literature related to ergonomic factors is scarce; thus, in this paper, the ergonomic factors are broadly classified under physical ergonomic factors (reach, vision, and strength analysis) and cognitive ergonomic factors (mental load and information flow).

Apart from the above mentioned factors, there are other factors such as prototyping purpose [55, 181], fidelity level [212], scale [54], and complexity [212] that needs to be considered before creating a prototype. However, no framework that combines the prototyping literature and HFE literature exists, which can help designers in exploring prototyping strategies for human-centered products. This paper proposes a novel prototyping framework to reduce the gap in the literature. Further, this framework also includes prototyping tools specific to human-centered design that can be used to fabricate prototypes. The hypothesis is that the pro-

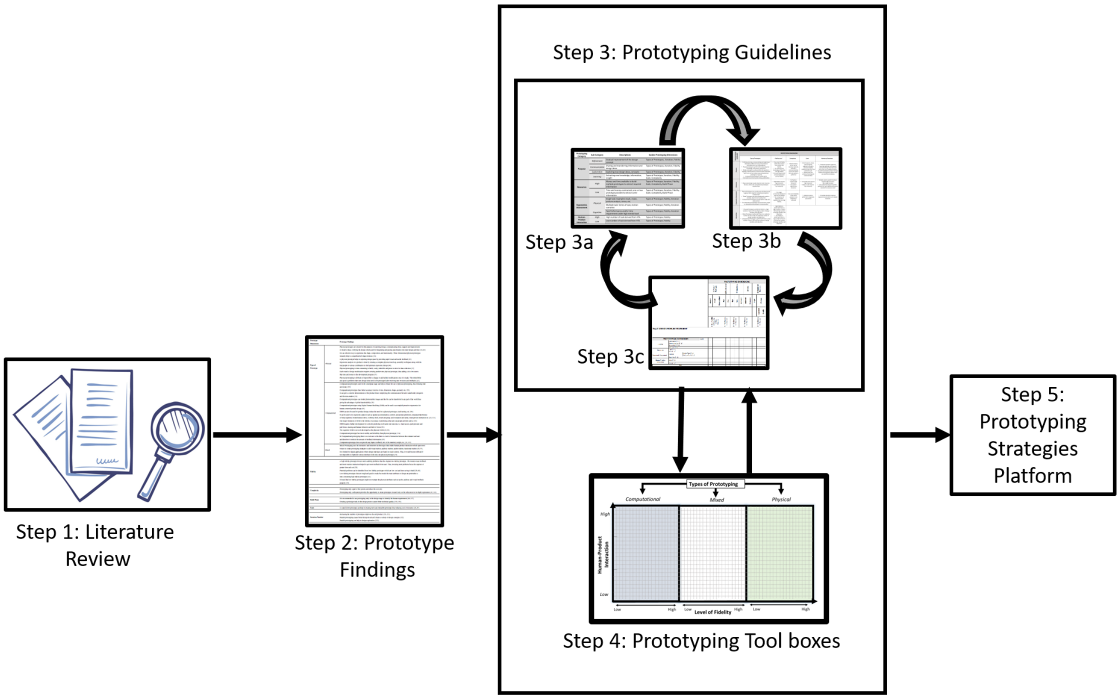

Figure 5.1: The Methodology to Develop the Proposed Framework

totyping theories *("why?")* and the prototyping tools *("how?")* will equip the designers to build better prototypes. Details of the framework are provided in the next section.

5.4 Methodology

It is found in the prototyping literature that the majority of prototyping frameworks are developed by following similar methodologies, based on surveying existing prototyping findings and the best practices. For example, Christie (2012) et al. performed an extensive literature review to determine the most critical prototyping factors and developed a list of questions that can be used to identify which factors have the most impact on a design project. The hypothesis was that the correct identification of the prototyping factors can help designers develop the appropriate prototyping strategy within available resources [66]. Similarly, Camburn et al. (2015) also reviewed prototyping literature rigorously to extract key findings and proposed six key heuristics. These were used to create a systematic method that designers can use while building prototyping strategies [54]. Also, Menold (2017) et al. extracted three major functions of prototypes and four specifications for a prototyping framework based on prototyping literature. The proposed prototyping framework had three key phases of Frame, Build, and Test, which can be used to guide designers through the prototyping process [166]. Furthermore, Lauff (2019) et al. performed a literature review to distill key prototyping aspects and used feedback from experts to create a prototyping canvas, which can help designers to plan purposeful prototypes by identifying the critical assumptions and questions [144]. In summary, the trend in the relevant prototyping studies starts with an exhaustive literature review to find critical prototyping factors. A similar approach is used in this research to build a framework that guides designers in their prototyping quests focusing on injecting HFE design principles into early design.

In this paper, we performed a similar approach, which is summarized in Figure 5.1, where the flowchart shows the steps taken to build the proposed Pre-Prototyping framework. Step 1 consists of a detailed literature review of prototyping definitions, taxonomies, findings, and guidelines. It also includes the literature review of HFE, prototyping in human-centered design, DHM, PSFs, and mixed prototyping. The information found in Step 1 is then filtered to extract information that is empirically validated, repeatable by the scientific community, and relevant to human-centered design. The filtered information is presented in Step 2, which contains the key findings in a tabular form, as shown in Table 2, in Appendix A. The raw information in Table 2 (Appendix A) is summarized and presented in Figure 1 in Appendix B so that it can be easily retrievable and usable in the following steps of the methodology.

In Step 2, we synthesized the information gathered from the literature review to develop the prototyping categories and prototyping dimensions, which are summarized in Figures 5.2 and 5.3. Later, the data was used for constructing Step 3, which is made of three sub-steps. In Step 3a Figure 5.2, the prototyping categories are presented. Prototyping categories can be viewed as the requirements or the questions that a prototype must fulfill or answer. There are four prototyping categories shown in Step 3a: (1) the purpose of prototyping, (2) available resources, (3) required ergonomic assessments, and (4) required human-product interaction. Step 3a also contains Prototyping Dimensions as shown in Figure 5.2, which can be viewed as the specifications by which the prototype must be created to fulfill the prototyping requirements. Step 3b is a matrix of prototyping categories and dimensions, as shown in Figure 5.4. This matrix can help the designer to understand how the prototyping categories and prototyping dimensions are connected via the prototyping guidelines.

Finally, in the last step of Step 3 (Step 3c), the "House of Prototyping Guidelines (HOPG)" is presented in Figure 5.5 which is loosely inspired by the House of Quality (HOQ) approach [115]. Designers can use the matrix, as shown in Figure 5.4, to select prototyping categories and prototyping dimensions based on the prototyping guidelines and fill out HOPG. After selecting the prototyping dimensions, Step 4 allows the selection of prototyping tools. Step 4 contains the *"know-how"* and toolboxes as shown in Figure 5.6 that provide practical knowledge to engineers to build prototypes. Step 3 and Step 4 provide the theoretical and practical knowledge respectively to engineers about prototyping strategies for human-centered products and workplaces during the conceptual design process. Finally, in Step 5, as shown in Figure 5.7, the Pre-Prototyping framework for human-centered design is presented by blending all the previous steps.

5.4.1 Step 2: Prototyping Findings

Table 2 in Appendix A and Figure 1 Appendix B are generated by summarizing and filtering the findings gathered from Step 1. The first column, containing Prototyping Dimensions as shown in Appendix A and Appendix B, is defined as the necessary factors to consider while creating prototypes. The prototyping dimensions can affect the quality of the prototype and the end product. These six prototyping dimensions are adopted from the prototype taxonomy created by Stowe (2008) [212] and Systematic Tool developed by Camburn et al. (2015) [54]. The second column lists the prototyping findings corresponding to the six prototyping dimensions. These findings are extracted from an extensive literature review by applying the three filters: (a) Prototype findings that are empirically validated,

(b) Prototyping findings that are repeatable and validated by the scientific community, and (c) Prototyping findings that are related to human-centered products. Step 2 also contains a summary of prototyping findings, as shown in Figure 1.

Prototyping Category	Sub-Category	Descriptions
Purpose	*Refinement*	Gradual Improvement of the design concept
	Communication	Sharing and transferring information and design ideas
	Exploration	Exploring new design ideas, concepts
	Learning	Extracting new knowledge, information, insight
Resources	*High*	Money and time available to build multiple prototypes to extract required information
	Low	Time and money constrained, one or two prototype possible to extract some information
Ergonomics Assessment	*Physical*	Single task: Examples reach, vision, posture analysis, stress, etc.
		Multiple task: Series of task, motion scenarios
	Cognitive	Task Performance and/or time requirement under high mental load
Human-Product Interaction	*High*	High number of task derived from HTA
	Low	Low number of task derived from HTA

Figure 5.2: Step 3a: Prototyping Category

5.4.2 Step 3: Prototyping Guidelines

In Step 3, the general guidelines for creating a prototype are influenced by the recent work of Lauff (2019) et al. and Camburn (2015) et al. [54, 55, 144]. Lauff (2019) et al. proposed a prototyping canvas based on the principles of purpose,

Prototyping Dimensions	Sub-Dimensions	Descriptions
Type of Prototype	*Physical*	It is the medium of prototype or how it is made. It can be either physical (cardboard, wood, etc.), computational (DHM, Sketchpad, etc.) and mixed (VR, AR, MoCap, etc.)
	Computational	
	Mixed	
Fidelity Level	*High*	It represent how accurately the prototype resembles the final product in terms of form, function, aesthetics
	Low	
Complexity	*Full*	The amount or potion of the product to be prototyped. For example, prototyping only the tip of the wing instead of the whole aircraft
	Sub	
Scale	*Increased*	It is the size of prototype in terms of form and function to be prototyped
	Same	
	Decreased	
Number of Iterations	*Single*	It is about the number of prototype to be created.
	Multiple	

Figure 5.3: Step 3a: Prototyping Dimension

resource, and strategy [144]. Camburn (2015) et al. performed a literature survey and suggested four common purposes for creating a prototype [55]. Step 3 is divided into three parts. Step 3a contains the prototyping categories and prototyping dimensions as shown in Figures 5.2 and 5.3. Prototyping categories help designers to understand the design problem at hand (i.e., what requirements the prototype must fulfill). In Step 3a, the need for building the prototype is realized, which is loosely similar to the *"Customer Requirement (What's?)"* in House of Quality (HOQ) [115].

A necessary part while building prototyping strategies is to identify what the objectives or questions are that the prototype is going to fulfill [119, 144]. How much resource available for prototyping? In addition to identifying purposes and resources in human-centered product prototyping, designers need to identify the type of ergonomic assessments and level of human-product interactions. Step 3a (Figures 5.2) helps designers to identify the purpose, resource availability, type of ergonomic assessment, and interaction levels.

PROTOTYPING CATEGORY	PROTOTYPING DIMENSIONS				
	Type of Prototypes	***Fidelity Level***	***Complexity***	***Scale***	***Number of iterations***
Purpose	• If refining, learning, communicating and exploring is adequately addressed using computational prototype than use computational • Physical prototype is preferred for extracting new knowledge, refinement, exploration • Mixed prototype is preferred when the product is digitally created however, tactile and other feed back which can not be created using computational prototype is required • Computational prototype is preferred for international communication among stakeholders	• If any level of fidelity satisfy the purpose then choose low fidelity • For learning new knowledge of function, use high fidelity • For quick ideation and concept exploration use low fidelity	• If the functions, forms can be learned, explored, refined or communicated by only a sub system then sub system is preferred	• If the functions, forms can be learned, explored, refined or communicated by unaltered scale, then use unaltered scale. • Altered scale can enhances learning and communication	• If multiple iterations improves learning, exploring, refining and communicating of functions and forms then use multiple iterations • If parallel prototyping reduces design fixation and improves ideation then use parallel prototyping
Resources	• Physical prototype usually requires most resources (finance, time) and computational prototypes requires least	• High fidelity requires high resources • Low fidelity requires less resources	• Full System requires high resources • Sub system requires less resources	• Increased scale requires high resources • Reduce scale requires less resources	• Multiple and/or parallel iterations requires high resources than single iteration • Use multiple iterations if benefits gained from each additional iteration exceeds the resources used
Ergonomics Assessment	• Physical Prototype can usually assess all physical and cognitive from single to multiple and simple to complex task • Mixed Prototype can assess moderately simple to complex physical and complex task • Computational Prototype is preferred for single and physical task • For infeasible and hazardous task assessment, mixed or computational prototype is recommended	• For single, unconstrained physical task use low fidelity • For a sequence of physical and/or cognitive task use high fidelity	• Use sub complexity if the whole product is not designed or assessed	• Unaltered scale is preferred in ergonomic assessment	• If multiple iteration improves ergonomic assessment use multiple iterations
Interaction	• Physical Prototype is preferred if there is a high number of task in HTA and high number of design variables and objectives • Mixed Prototype is preferred if there is a moderate number of task in HTA and moderate number of design variables and objectives • Computational Prototype is preferred if there is a low number of task in HTA and low number of design variables and objectives	• High Fidelity is preferred if there is high number of task in HTA and high number of design variables and objectives • Low fidelity is preferred if there is low number of task in HTA and low number of design variables and objectives			

Figure 5.4: Step 3b: Prototyping Category and Prototyping Dimension Matrix

The natural progression after finding out *what* the prototype must fulfill is to find out *how* the prototype can fulfill the requirements. Prototyping dimensions, as shown in Figure 5.3, include the list of specifications that designers can use to create a prototype. Prototyping dimensions are similar to the concept of *"Engineering Requirements"* in HOQ. From the literature review, six prototyping dimensions, namely, type of prototype, fidelity level, complexity, build phase,

				PROTOTYPING DIMENSIONS												
				(1) Type of Prototype			(2) Fidelity Level		(3) Complexity		(4) Scale			(5) Number of Iterations		
				Physical	Computational	Mixed	High	Low	Full	Sub	Increased	Same	Decreased	Single	Multiple	
															Sequential	Parallel
				0 = Not Feasible, 1= Feasible, 2= Most Feasible			0 = Not Desired, 1 = Desired		0 = Not Desired, 1 = Desired		0 = Not Desired, 1 = Desired			0 = Not Desired, 1 = Desired		
PROTOTYPING PROBLEM STATEMENT																
PROTOTYPING CATEGORY			*Weight*													
Purpose	*Refinement (0-1)*															
	Communication (0-1)															
	Exploration (0-1)															
	Learning (0-1)															
Resources	*High (0-1)*															
	Low (0-1)															
Ergonomic Assessment	*Physical*	*Single Task (0-1)*														
		Multiple Task (0-1)														
	Cognitive															
Human Product Interaction	*High (0-1)*															
	Low (0-1)															
Sum																

Figure 5.5: Step 3c: House of Prototyping Guidelines

scale, and the number of iterations, are identified that designers can use to create a prototype. These prototyping dimensions are primarily leveraged from the prototyping taxonomy developed by Stowe (2008) [212] and the Systematic Tool proposed by Camburn (2015) et al. [54]. Since the proposed methodology is focusing on a pre-prototyping approach, the build phase is always at the early design stage; thus, it is not included in later steps.

Step 3b, as shown in Figure 5.4, is a matrix of prototyping guidelines for the corresponding prototyping categories and prototyping dimensions. The prototyping categories and prototyping dimensions are taken from the Figures 5.2 and 5.3, and the guidelines are taken from 2 in Appendix A and Appendix B. The prototyping guidelines embedded in the matrix can help designers identify which prototyping dimensions are suitable for a particular prototyping category. Finally, in Step 3c, the prototyping guidelines extracted in Step 1 and 2, the prototyping categories, prototyping dimensions, and the matrix proposed in Step 3a and 3b are tied together to form House of Prototyping Guidelines (HOPG) as shown in Figure 5.5. HOPG integrates all the information from the previous steps and puts it in a schematic where designers can use the theoretical guidelines in creating a prototype. Similar to the House of Quality approach, HOPG has prototyping requirements (i.e., prototyping categories *(what?)*) in one section and prototyping specifications and (i.e., prototyping dimensions *(how?)*) in another section. In HOPG (Figure 5.5), the designer starts with understanding the prototyping problem statement and identifies the prototyping requirements. The problem statement guides the designer to complete the prototyping category. The designer then chooses the appropriate prototyping categories and inserts the value of either 0 or 1 in the weight column. Next, the designer chooses the prototyping dimensions corresponding to each prototyping category using the matrix provided in Figure 5.4 and rates them using the rating provided in HOPG in Figure 5.5. The last step in Step 3c is to select the prototyping dimensions with the highest value. The value of each prototyping dimension is calculated using the following equation (See 5.2.

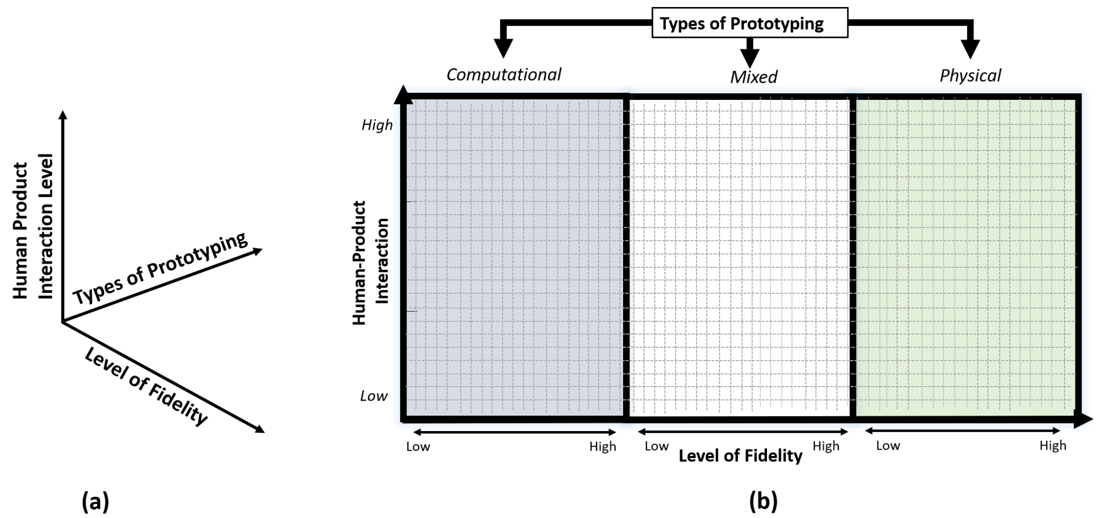

Figure 5.6: Step 4: The Prototyping Toolbox

$$\begin{aligned} Sum &= Weight \times Rate \\ Weight &= \text{prototyping categories} \\ Rate &= \text{prototyping dimensions} \end{aligned} \tag{5.1}$$

For example, in the type of prototype category, if physical, computational, or mixed prototyping gets values of 2, 3, and 5, respectively, then the mixed prototype becomes the preferred dimension because it got a higher score than that of physical and computational. Completing Step 3c using the HOPG equips designers with theoretical knowledge on how to build a prototype.

The next step in the proposed methodology is to generate the practical tools *"know-how"* on how to build the prototype, which is given in Step 4.

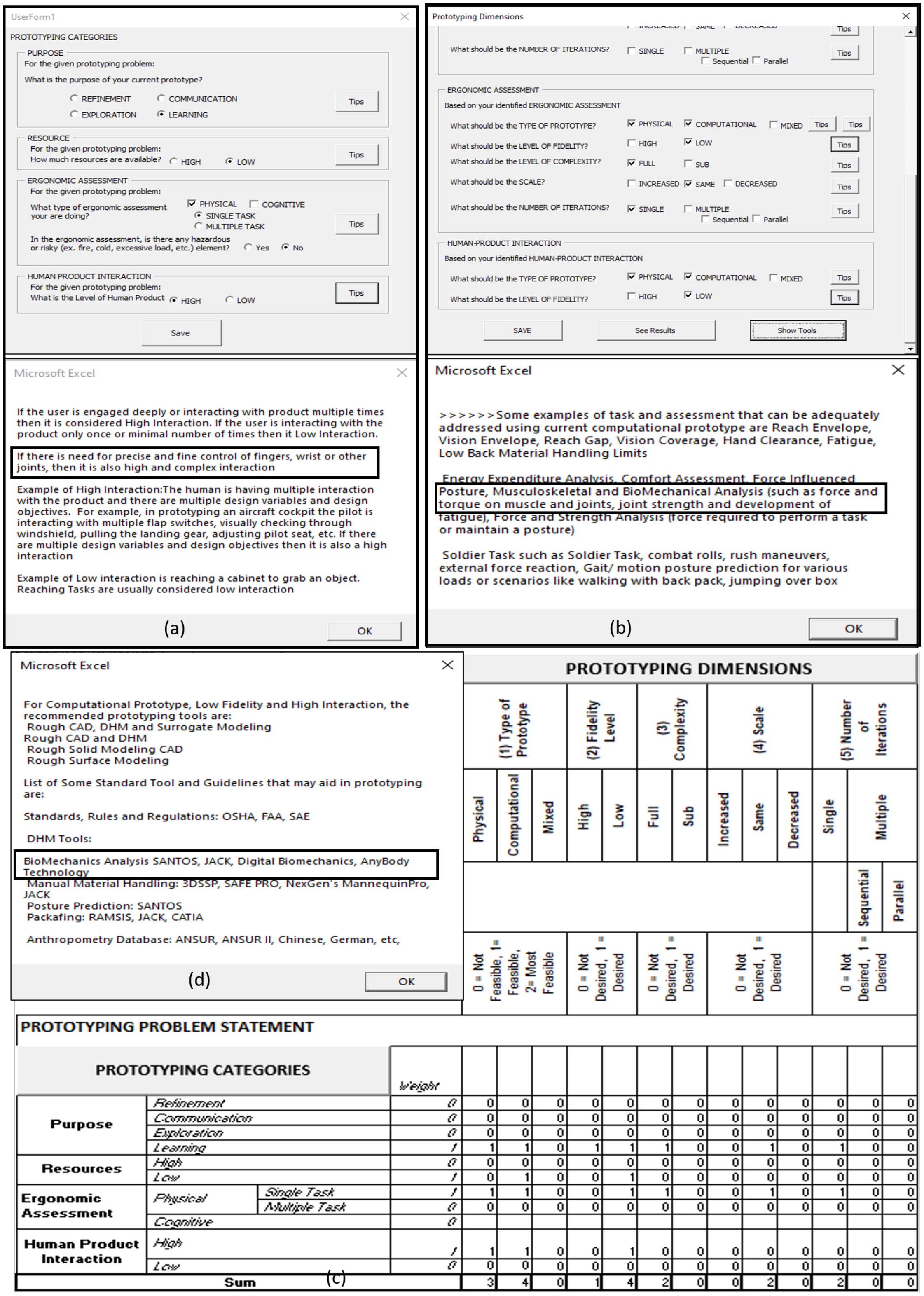

Figure 5.7: A Platform to Represent the Prototyping Framework

5.4.3 Step 4: Prototyping Tool Boxes

Step 1 to 3 provides the theoretical knowledge and guidelines to develop a prototype for the design of human-centered products or workplaces. It is found in the literature that designers who do not have extensive experience in prototyping have different views and perceptions about prototyping. Deininger (2017) et al. found that novice engineers' conception of prototyping varies widely [74]. Menold (2017) et al. performed a survey and found that novice designers have an inaccurate and incomplete perception of prototyping purpose and prototyping activities [166]. Similarly, Cristie (2012) et al. stated that the success of prototyping depends on the expertise of those who perform prototyping activities [66]. This is also evident in the study of Menold (2017) et al. In their research, even though multiple groups of student-created prototypes following the same theoretical prototyping strategies, prototypes were created of quality, ranging from high to low among the different groups [166]. These findings show that providing only theoretical guidelines about prototyping to inexperienced designers is not enough to warrant a high-quality prototype. Theoretical prototyping guidelines are broad and general, making it challenging to find the proper method or tool for modeling or fabrication. Hence, inexperienced designers rely on their experiences and creativity to build prototypes. Thus, the quality of prototypes varies from one designer to another, even though the same theoretical prototyping strategy is provided. To minimize the prototypes' quality variation, we hypothesized that practical *"know-how"* and toolboxes should be added to the prototyping strategy. The proposed prototyping strategy fills up this gap by introducing a prototyping toolbox in Step 4, as shown in Figure 5.6.

One can consider the prototyping toolbox as an inventory of tools and technologies that the designers can use to create prototypes. It is composed of three axes which are “Human-Product Interaction”, “Types of Prototype”, and “Level of Fidelity” as shown in Figure 5.6(a). The Type of Prototype and Fidelity Level of Prototype are leveraged from the Hierarchical Morphological Prototyping (HMP) Taxonomy [212], and Human-Product Interaction Level is leveraged from Human Aspects of Design as proposed by Duffy (2007) [88]. The three axes system classifies the tools that fit inside the toolbox for prototyping human-centered products.

Within the toolbox, the type of prototype is divided into three discreet types: physical, computational, and mixed. Furthermore, the fidelity level and human-product interactions are considered in a continuum, ranging from low to high. In theory, the fidelity level and human-product interaction axes can be divided into infinitely many sections to accommodate any appropriate prototyping tools. Due to the continuum of fidelity and human-interaction level, rapid changes in technology, and availability of resources (time, cost, and skill), it is not possible to list all the past, current, and future tools that can go inside the toolbox. Hence, a blank toolbox is proposed in Figure 5.6(b). It is left to designers to fill the toolbox with the tools corresponding to the design problem and the availability of resources. Designers or stakeholders can fill up the toolbox according to their specific product design requirements and available resources such as time, finances, human skills, tools, and then navigate within the toolbox using the theoretical guidelines from

Step 3 to select the right tool.

5.4.4 Step 5: Human-Centered Design Pre-Prototyping framework

Step 5 presents the proposed Pre-Prototyping framework, which combines both the theoretical guidelines *"why?"* from Step 3 and the practical *"know-how"* from Step 4 as shown in Figure 5.1. The framework is developed using a Microsoft Excel User-Form so that designers can interact with a graphical user interface. Figure 5.7 shows a snippet of the Excel User-Form. Delivering the framework in the form of an Excel User-Form provides multiple advantages. First of all, Excel User-Form saves time for the designers while exploring the appropriate prototyping categories and prototyping dimensions (Figures 5.2 and 5.3), related guidelines (Appendix A and Appendix B and Figure 5.4), doing manual calculations in HOPG (Figure 5.5, and navigating within the toolboxes (Figure 5.6, Figures 5.2 and 5.3). Secondly, the Excel User-Form also partially automates the process and provides the framework in a more user-friendly way. It starts with a blank HOPG, and as the designer selects the prototyping categories and prototyping dimensions, the blank HOPG boxes fill up. The first step in this Excel User-Form is to understand the given prototyping design problem. Next, the designer clicks the *"Prototyping Categories"* button and a window (Figure 5.7(a)) pops up. The pop-up window shows the four prototyping categories and the sub-categories, respectively. The corresponding prototyping guidelines for each prototyping category are embedded in the User-Form and can be accessed by the *"Tips"* button, as shown in the pop-up window below *"Prototyping Categories"*. After selecting all the appropriate categories, the designer can *"Save"* the selections, close the window, and move to prototyping dimensions. Clicking the *"Prototyping Dimensions"* will enable another pop-up window showing the five prototyping dimensions. In this window, the designer will select the prototyping dimensions for each prototyping category that fulfills the prototyping requirement, as shown in Figure 5.7(b). This window also has tips that can assist designers in selecting the correct prototyping dimensions. After going through the prototyping dimensions, the designer can save the information and can see the resulting prototyping dimensions by clicking the *" See Results"*, which will automatically fill the HOPG in, as shown in Figure 5.7(c); thus, presenting the resulting prototyping dimensions. Then, the designer can also see the corresponding tools that can be used to build the prototype by clicking the *"Show Tools"* button, as shown in Figure 5.7(d) without going to the toolbox. A case study to illustrate the Pre-Prototyping framework is given in Section 4.

5.5 Case Study

A case study is presented in this section to demonstrate how the prototyping framework can be used to create the appropriate prototyping strategy for a given prototyping problem. The prototyping problem is taken from an established literature [161]. The prototyping problem is as follows:

You are to conceptualize a prototyping strategy that can be used for the ergonomic assessment of an ultrasound probe. You will assess how a healthcare *professional grips the probe in terms of comfort and performance. You are given low resources.*

The first step in formulating the prototyping strategy using the prototyping framework is to thoroughly understand the prototyping problem and its requirements. The information from the prototyping statement is used to derive the *"Prototyping Categories"*. The exact Figure 5.7 can be used to demonstrate the prototyping strategy of the prototyping problem as it is populated based on this problem to save space.

The second step in formulating the prototyping strategy is to go through the *"Prototyping Categories"*. Clicking the *"Prototyping Categories"* brings Figure 5.7(a),. where the prototyping and HFE guidelines to select the *"Purpose, Resource, Ergonomic Assessment, and Human-Product Interaction"* are embedded in the *"Tips"*. For *"Purpose"*, *"Learning"* is selected because the *"Tips"* says if the purpose is to know new information,then *"Learning"* should be selected. In this problem, the designer is looking for new information to assess the ultrasound probe. It is given that the resources available to build the prototype are low, so the *"Low"* option is selected for *"Resource"*. Next, *"Physical and Single Task"* is chosen as the prototyping problem does not have any design component that is cognitive related, and it is assumed that the healthcare worker will use the ultrasound probe only once to perform the checkup. An example of the prototyping and HFE guidelines embedded in the *"Tips"* for *"Human-Product Interaction"* is presented in the pop-up window below *"Prototyping Categories"* (Figure 5.7(a)) which indicates that if there are precise and fine finger control, then it should be considered as high-level interaction. Hence *"High Human-Product Interaction"* is selected. Finally, the selections are saved by clicking the *"Save"* button and closing the window.

The third step involves going through the *"Prototyping Dimensions"*, as shown in Figure 5.7(b). In this window, each *"Prototyping Dimension"* is selected based on the previously identified *"Prototyping Categories"* and *"Tips"*. The first one is *"Type of Prototype"*, and it has three options, which are *"Physical, Computational and Mixed"* prototype. According to the given prototyping problem and tips, the *"Mixed Prototype"* is the least viable as it lacks the tactile feedback and biomechanical analysis needed for this problem. So *"Mixed Prototype"* is not selected for any corresponding *"Prototyping Categories"*. For the *"Purpose"*, both the *"Physical"* and *"Computational"* are chosen as for learning new information, since both of these options are viable. For *"Resource"*, *"Computational"* is chosen over *"Physical"* as it usually needs fewer resources. Since the resource is low for the given problem, *"Computational"* option is applicable. Next, for *"Ergonomic Assessment"*, both the *"Physical"* and *"Computational"* can be chosen because most assessment can be done using physical prototype. Some assessments such as biomechanical analysis of muscles and joints of fingers can be executed as shown in the *"Tips"* window in Figure 5.7(b) under *"Computational"* category. Finally, for *"Human-Product Interaction"*, both types of prototypes are chosen. It is because *"Physical Prototype"* is generally suitable for *"High"* and *"Low"* interactions. However, *"Computational Prototype"* usually does not generate *"high-level interaction"* analyses, like precision gripping, automatically. However, if the designers know the type of grip, then they can manually manipulate the finger joints to mimic the actual grip.

The next *"Prototyping Dimension"* is the *"Level of Fidelity"*. Both the *"High"* and *"Low"* options are chosen because for learning new information, high fidelity is preferred. However, if there is a need for a quick assessment and the fidelity level is not clear, then *"Low"* fidelity is chosen by default. For *"Resource"*, *"Low"* fidelity level is chosen because the embedded guidelines show that the low fidelity requires low resources and vice versa. For *"Ergonomic Assessment"* and *"Human-Product Interaction"*, *"Low"* option is chosen as there is only one physical ergonomic assessment to be performed and only one human-product interaction is present (i.e., a single healthcare worker and one device). The next dimension is *"Level of Complexity"*, where *"Full"* is chosen because a full model of the ultrasound probe is required for ergonomics assessments. Similarly, *"Same"* is chosen for *"Scale"* because an altered scale would give incorrect results. Finally, *"Single"* iteration number is selected as only one iteration is enough to get the results and also because the given resource is low.

Once all the *"Prototyping Dimensions"* are selected, the *"Save"* button is pressed, and the numbers are crunched inside the HOPG as shown in Figure 5.7(c). The final calculations for the *"Prototyping Dimensions"* can be seen by clicking the *"See Result"* button. Figure 5.7(c) shows that *"Computational Prototype, Low Fidelity, Full Complexity, Same Scale, and Single Iterations* are the recommended prototyping dimensions as their *"Sum"* came out to be the maximum. The recommended tools can be seen by pressing the *"Show Tools"* button, as shown in

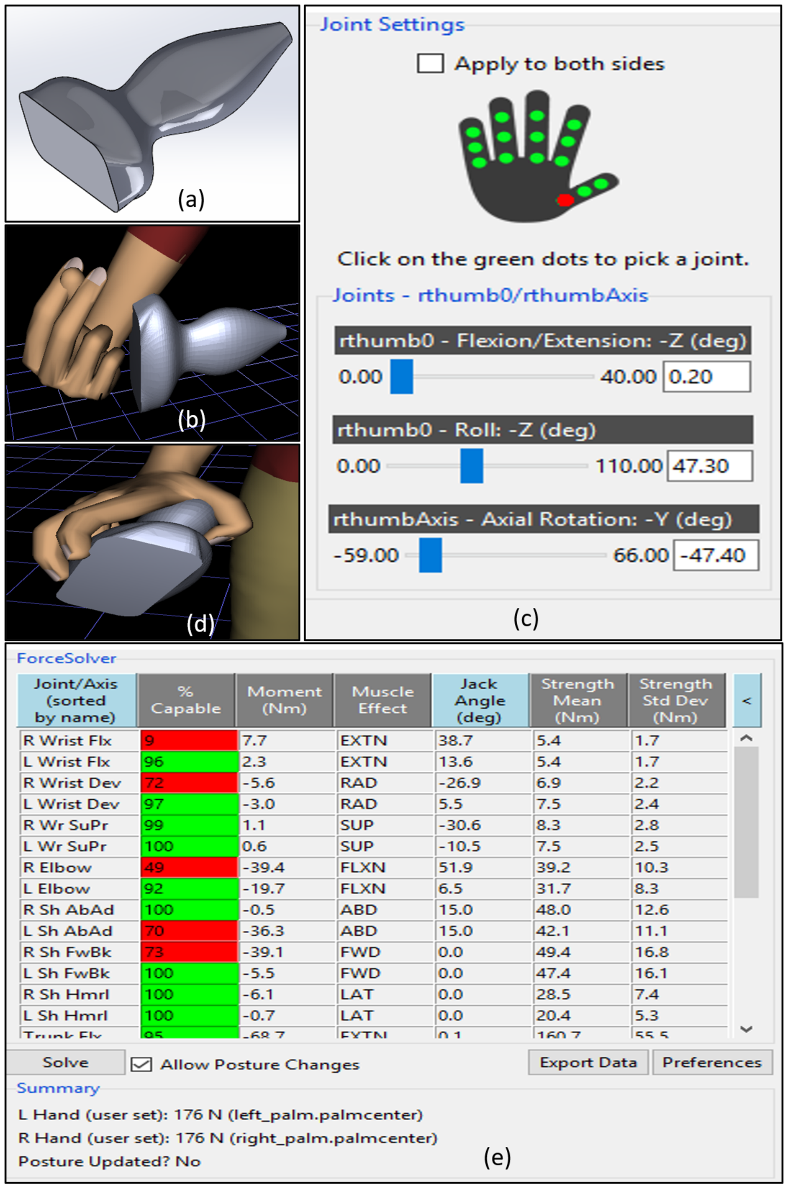

Figure 5.8: Prototype Created Using the Prototyping Strategy from the Pre-Prototyping framework

Figure 5.7(d). It shows a list of tools such as *Rough CAD, DHM and Surrogate Modeling"* and *Rough CAD and DHM"*, which can be used for prototyping. Further, it recommends specific DHM tools such as Santos or Jack Siemens, which can execute the required computational ergonomics analysis.

The prototyping strategy described above is used to create the product prototype as shown in Figure 5.8. The ultrasound probe (Figure 5.8(a)) is created using CAD and then transferred into DHM software. It is mentioned before that DHM can not simulate the fine movement of fingers (i.e., grip), so a grossly incorrect grip is shown in Figure 5.8(b) when an automatic grip command is given. So, the grip is corrected by manually manipulating the fingers and joints as shown in Figure 5.8(c), and the correct three-finger grip is shown in Figure 5.8(d). Finally, the biomechanical analysis of the joints is shown in Figure 5.8(e), which can be used to assess the comfort and performance of the healthcare worker for using the ultrasound probe.

5.6 Validation of the Pre-Prototyping Framework

The proposed framework can be validated by a combination of quantitative and qualitative analysis. In this study, the quantitative analysis is carried out by measuring the *"Prototyping Success"* between the Intervention group and the Control group. Both groups will be tested using multiple but identical prototyping problems. The prototyping problems and their solutions are taken from established literature. The Intervention group will use the Excel User-Form as shown in Fig-

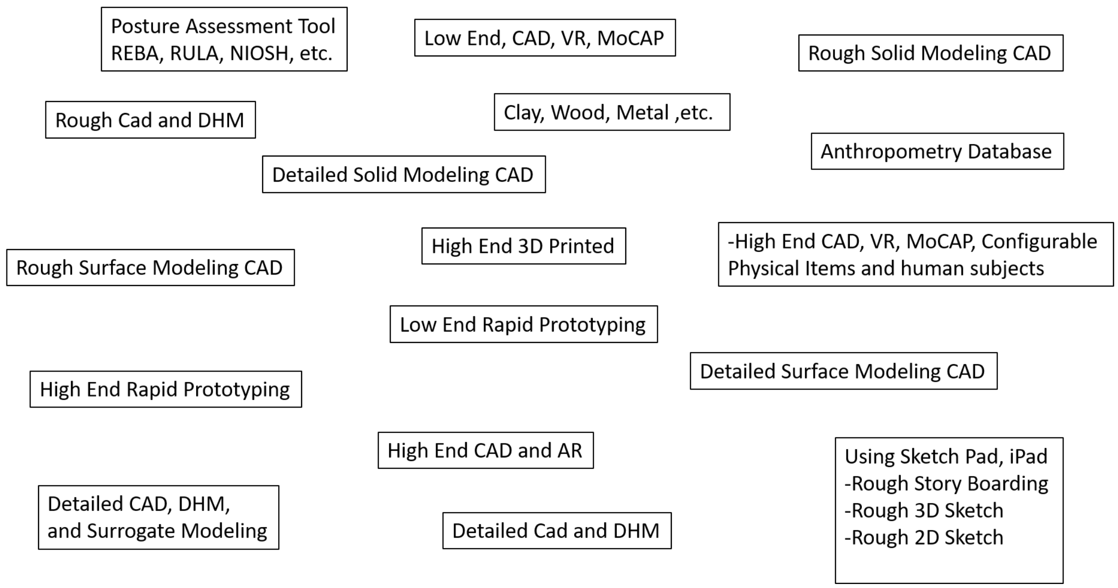

Figure 5.9: First List of the Toolbox

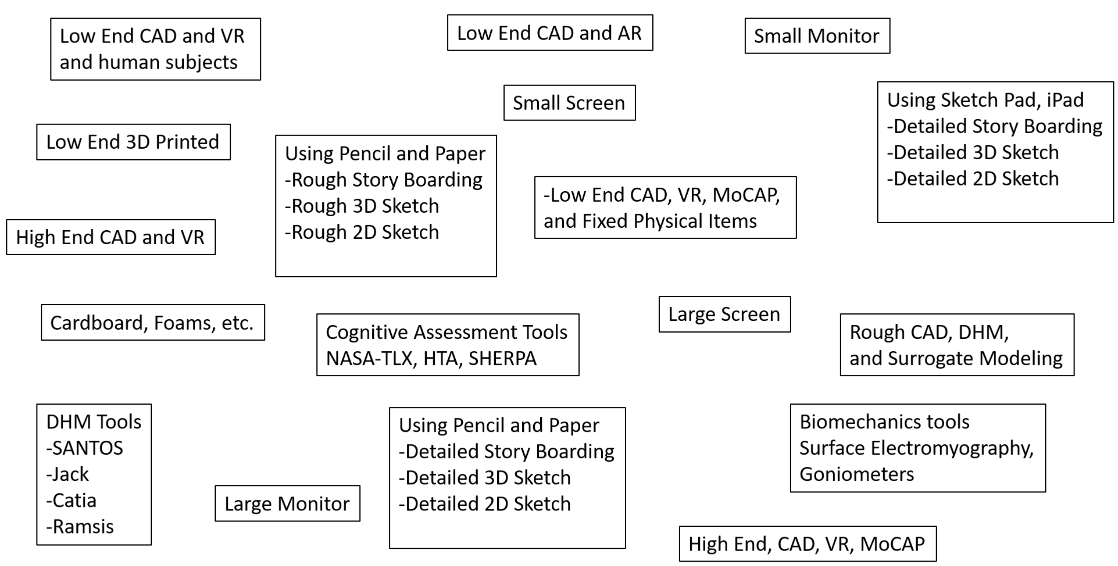

Figure 5.10: Second List of the Toolbox

ure 5.7, and the Control group will only have a list of prototyping tools as shown in Figures 5.9 and 5.10. The following equation measures prototyping success.

$$\begin{aligned} \mathit{Prototyping\ Success}\ (4) = {} & \mathit{Type\ of\ Prototype}\ (2) \\ & + \mathit{Level\ of\ Interaction}\ (1) \\ & + \mathit{Level\ of\ Fidelity}\ (1) \end{aligned} \tag{5.2}$$

The values in the parenthesis represent the maximum values possible in each category. Correct identification of the level of interaction and fidelity will receive a score of one. The type of prototype has the highest score of two, as some prototyping problems can be prototyped by more than one type of prototype. The validation of the methodology is carried out by observing whether there is a statistical difference between the Intervention group and the Control group regarding conceptual prototyping as shown in Figure 5.11. The null hypothesis is that the Intervention and Control group will have a similar average prototyping success score, whereas the alternative hypothesis is that the Intervention group will have a significantly different (probably higher) average prototyping success score compared to that of the Control group. The Intervention group will be given the proposed methodology (via framework - User Excel Form), and the Control group will not be given any methodology but a toolbox that contains the same prototyping tools as given to the Intervention group. Then, the Intervention group and the Control group will be given the same prototyping problems. The experiment will explore whether the Intervention group and the Control group select the same set of tools or not. Successful prototyping for the Intervention group is measured as

Type of Test	Measured Data	Hypothesis Tested (PRQ 1, 2, 3)	Statistical Test
Conceptual Prototyping	Prototyping Success Score	$H_O: \mu_1 = \mu_2$ Designers who use the methodology will have same prototyping success as designers who do not use the methodology. $H_A: \mu_1 \neq \mu_2$ Designers who use the methodology will have a significantly different prototyping success compared to designers who do not use the methodology	Independent Samples t Test

Figure 5.11: Summary of the Test Plan

the selection of correct prototyping categories and prototyping dimensions.

5.7 Experimental Setup

Twelve prototyping problems are chosen to test the Intervention and Control group. These twelve problems are selected in such a way that they can test the whole range of the Prototyping dimensions, Prototyping Categories, and Toolbox, as shown in Figure 3 in Appendix D. The twelve prototyping problems and their solutions are also given in Appendix D.

A total of eighteen participants took the experiment. Participants' selection criteria included the following. The participants should be at least junior level or higher and of engineering background so that they have some idea or heard about prototyping before. Graduates who are working as professionals are also allowed to take the experiment. These participants were then randomly chosen to be either in the Intervention or Control group.

The experiment is computer-based for both groups. The Intervention group was given the proposed Pre-Prototyping framework in an Excel User-Form, tutorials and examples on how to use the Prototyping Framework Excel form, Prototyping Problem Statements (Appendix D), and instructions on how to take the test. On the other hand, the Control group was given the list of Toolbox, Prototyping Problem Statements (Appendix D), and instructions on how to take the test. The purpose was to see how the Prototyping Success Score for both the group when one group uses the proposed Pre-Prototyping framework and the other does not and only relies on experience and intuition.

Table 5.1: Average Prototyping Success Score of the Intervention Group

Participants	1	2	3	4	5	6	7	8	9
Intervention Group Prototyping Score	3.83	3.333	3.500	3.917	2.917	3.667	3.500	3.250	3.333

Table 5.2: Average Prototyping Success Score of the Control group

Participants	1	2	3	4	5	6	7	8	9
Control group Prototyping Score	3.333	3.083	3.000	2.667	2.500	2.917	3.00	2.667	2.583

5.8 Result

The Prototyping Success Score for each of the participants in the Intervention and Control group is measured using Equation 5.2. The Prototyping Success Score for both groups is given in Tables 5.1 and 5.2. The Descriptive Statistics of the Prototyping Score are presented in Table 5.2, including the number of participants, mean, confidence interval (CI), median, standard deviation, Skewness, Kurtosis,

Table 5.3: Descriptive Statistics

Descriptors	**Statistic**
N	18
Mean	3.125
95% Confidence Interval (CI)	2.931
	3.318
Median	3.083
Standard Deviation	0.388
Skewness	0.195
Kurtosis	-0.476
Shapiro-Wilk Test for Normality	0.973

and Shapiro-WilkTest for Normality. From Table 5.2, it is found that the absolute value of Skewness is less than 0.8, the absolute value of Kurtosis is less than 2.0, and the p-value in the Shapiro-Wilk test is not significant ($0.973 > 0.05$). These values verify the normal probability distribution of the data and satisfy one of the major assumptions of the independent sample t-test. Additionally, the histogram, Q-Q plot and the boxplot in Figures 5.12, 5.13, and 5.14 show that the histogram is approximately bell-shaped, points are fairly close to the line in the Q-Q plot and there are no outliers in the boxplot which visually shows the normal probability distribution of the data. Another assumption of the t-test is that the variances of the two populations are equal. Levene's test is performed to examine the variances as shown in Table 5.4. It is found that the p-value of Levene's test is not significant ($0.994 > 0.05$). This proves that the variances are equal and satisfies the t-test assumptions.

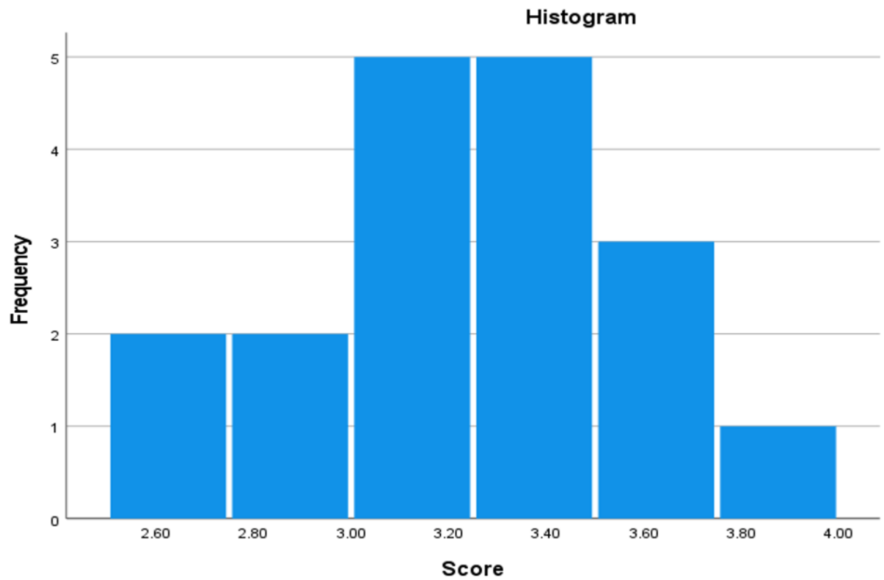

Figure 5.12: Histogram of the Data

Table 5.4: Independent Samples t- test of the Prototyping Success Score

	Levene's Test for Equality of Variances		**t-test for Equality of Means**					**95% CI**	
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Equal Variances Assumed	0.000	0.994	3.896	16	0.001	0.527	0.135	0.240	0.814

After the t-test assumptions are met, the independent sample t-test is carried out, and the results are tabulated in Table 5.4. The t-value is 3.896 and the p-value is 0.001 ($0.001 < 0.05$). The mean difference between the Intervention and Control group is 0.527 as the Intervention group mean Prototyping Score is 3.403 and the Control group mean Prototyping Score is 2.916.

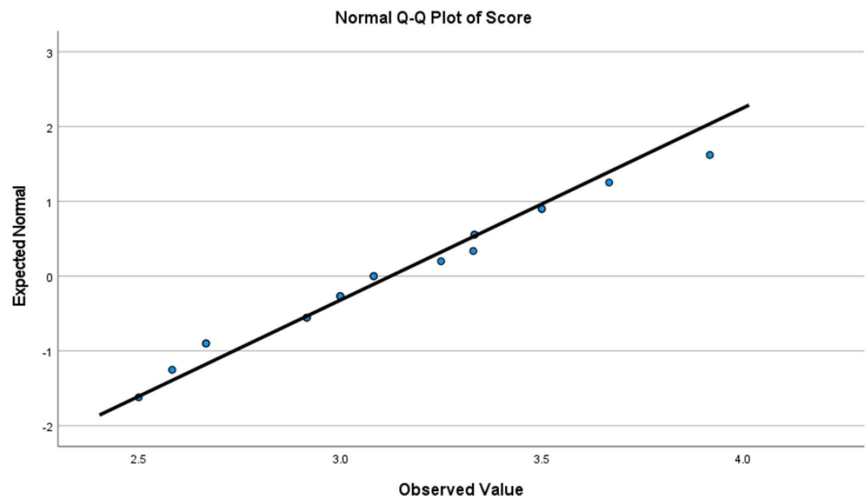

Figure 5.13: Q-Q Plot

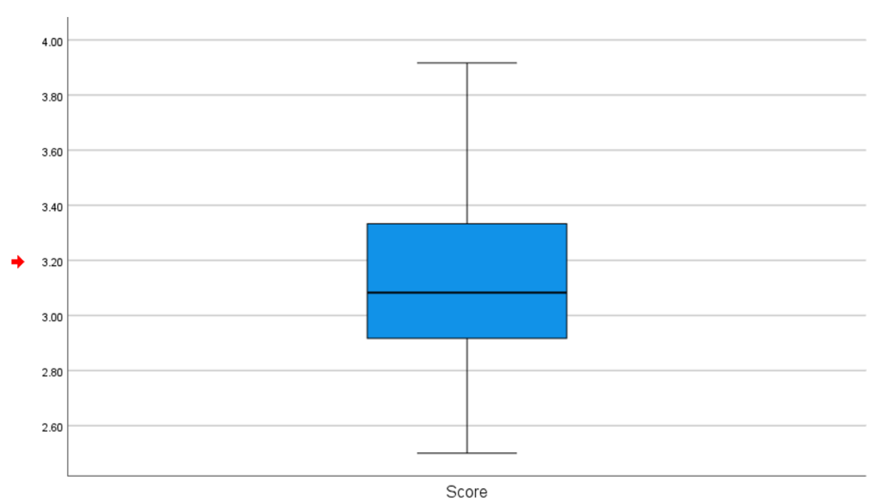

Figure 5.14: Box Plot

5.9 Discussion

The proposed methodology combines the prototyping literature and HFE guidelines to develop a Pre-Prototyping framework for the design of human-centered products and workplaces. The Pre-Prototyping framework provides strategies that include the theoretical knowledge and practical *"know-how"* toolbox. Using the House of Prototyping Guidelines (HOPG), designers can identify the theoretical scaffolding (i.e., the prototyping categories and dimensions). Next, the theoretical scaffolding can be used to navigate through the toolbox and identify the tools required to build the prototype. Further, the prototyping theory and the toolbox is integrated and presented via Microsoft Excel User-Form so that the framework becomes user-friendly and easy to implement.

The proposed Pre-Prototyping framework fills up the research gap of *"how to build a prototype for human-centered product"* by providing systematic guidelines which contain both the theory and practical knowledge on how to build a prototype. The existing prototyping frameworks do not integrate human factor engineering guidelines. Further, they primarily guide the designers by prompt-based open-ended questions instead of giving specific guidelines. It makes these frameworks hard to implement, and designers are forced to rely on their experience and intuition. These shortcomings of the current prototyping frameworks cause different designers to create different quality of prototypes even though they are using the same prototyping framework and working on the same prototyping problem.

A case study for assessing the ultrasound probe is presented to demonstrate a step-by-step walk-through of the prototyping framework. The resulting prototyping strategy using the proposed prototyping framework is in agreement with the prototyping strategy from Mazzola et al. (2017) [161]. Mazzola et al. (2017) created both physical and computational prototypes to assess the ergonomics of the ultrasound probe. However, the justification for why the prototypes are built the way they are built, i.e., a physical and computational prototype is missing. The proposed prototyping framework provides step-by-step guidelines and justification for the prototyping strategy. For example, the framework suggested a computational prototype such as CAD and DHM is a feasible solution given the limited resources. However, it also cautioned that DHM has poor fidelity in fine grip or complex finger movement and manual manipulation of the fingers is suggested. This example of specific suggestions is useful to create the right type of prototype especially for designers who are not experienced with Human Factors and Human-centered design.

It is hypothesized (PRH 1, 2, and 3) that since the proposed Pre-Prototyping framework generates systematic specific guidelines, it can lead the designers in the right direction by reducing the reliance on heavy guesswork. Designers who have the head start on building the correct prototypes can answer questions regarding human-centered products earlier. The systematic guidelines can save resources regarding cost and time as the designers start in the right direction and reduce dependency on trial and error. To test these primary hypotheses (PRH 1, 2, and 3), a validation study is carried out. From the study, it is found that the average

Prototyping Score of the Intervention group is 0.527 more than that of the Control group for the same 12 prototyping score. The t-value is 3.896 and the p-value is 0.001, i.e., less than 0.05. The independent sample t-test demonstrates that there is a significant difference between the Intervention and Control group's Prototyping Score and the Prototyping Score of the Intervention group is higher. In other words, the Pre-Prototyping framework containing the theoretical guidelines and practical tools assists designers in forming better prototyping strategies than designers who do not use the proposed Pre-Prototyping framework.

The usefulness of the proposed prototyping framework is that a designer who does not have domain expertise, years of experience, or the resources to do trial and error, can create the prototype using the Pre-Prototyping framework to accomplish the required ergonomic assessment. As demonstrated in the case study, the framework provides guidelines and reasoning to *"Why?"* and *"How"* to build the prototype. Additionally, the prototyping framework will provide consistent and standard prototyping strategies regardless of the user's knowledge and experience because the framework is based on systematic steps and guidelines. Typically, designers rely on trial-and-error during prototyping activities to find out the correct prototyping strategy, which often causes a waste in resources and variance in quality. Generating the correct prototyping strategy using the prototyping framework before doing any hands-on activity can save resources and improve product quality.

5.10 Limitation and Future Work

One of the limitations of this study is the broad classification of the human factors measures into either physical and cognitive means. There are around a hundred physical and cognitive human factors measures, and it is challenging to include all of them in the proposed framework. Additionally, there are no prototyping guidelines on how to address each of the hundred human factors measure while building the prototype. Thus, it is not possible to include these factors in the framework. Another probable shortcoming is in the prototyping theories used to create the House of Prototyping Guidelines. Although an extensive literature review is performed to find the important prototyping factors, it is not fully proof and perhaps some prototyping factors might be overlooked. However, a significant set of critical prototyping factors are integrated into the framework. Another limitation is that the toolbox needs to be filled up by the designer. It is because there are simply too many tools in the literature to be included in the framework and it is best for the designers to select the tools according to their available resources, expertise, and prototyping problem at hand. The proposed framework provides systematic guidelines to build a prototype so that designers do not need to rely on intuition. However, the designers still need some experience and creativity and should use the framework as a guideline to conceptualize prototyping strategies before jumping into hands-on activity.

There are numerous research routes to take from here on for future work. One interesting future work to consider is an alternative approach of making the Pre-

Prototyping framework domain-specific instead of integrating all prototyping and human factors into it. The focus will be on specialization instead of generalization. For example, a specialized framework can be created by targeting different domains/industries such as aviation, automobile, and sports equipment industries. The specialized framework can be more focused on specific ergonomics Interventions than that of a generalized Pre-Prototyping framework. Another possible future work is to make the Pre-Prototyping framework smart by incorporating artificial intelligence. The goal is to make the Pre-Prototyping framework autonomous so that it will suggest prototyping strategies based on the given prototyping problem automatically without the need for a designer to go through the framework step by step.

Chapter 6: A Conceptual Prototyping Framework for Integrating Human Factors Early in Product Design

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6.1 Abstract

A knowledge base that integrates human factor engineering (HFE) principles and prototyping best practices for the design of human-centered products does not exist. This study fills this gap by proposing a prototyping framework to unify HFE principles and prototyping guidelines along with a prototyping toolbox. The framework is based on the House of Prototype Guidelines (HOPG), which introduces "Prototyping Categories and Dimensions" that are used for understanding the prototyping requirements and identifying the specifications that can be used to build a prototype. Additionally, a prototyping toolbox is introduced to classify tools and technologies to build the proposed prototype. The HOPG and prototyping toolbox are integrated via an MS Excel User-Form, which offers a systematic selection filter based on user input. The overall goal of this framework is to guide the prototyping activities in the right direction before the actual hands-on prototyping activity starts. Further, a cost-benefit analysis tool is proposed to calculate the value of the prototype by measuring the information gained and the resources spent. The cost-benefit analysis helps designers in narrowing down the prototyping options. A prototyping problem taken from the literature is used as a case study to demonstrate the usability and efficacy of the framework. A validation study is conducted to observe and compare the prototyping strategies developed by the Intervention and Control group. It is found that, through the Prototyping Score test and the prototyping experience of both groups, the conceptual prototyping framework guides and assist designers in developing better prototyping strategies

than those who only rely on intuition.

Keywords: Design, Prototyping, Human-Centered Design, Human Factor Engineering, Cost-Benefit Analysis

6.2 Introduction

A prototype is defined as "A physical or digital embodiment of critical elements of the intended design, and an iterative tool to enhance communication, enable learning and inform decision-making at any point in the design process" [145]. Prototyping is one of the most fundamental keystones in the design and product development process [231]. Companies spent billions of dollars in the research and development (R&D) activities for product development. However, 40-46% of these resources are wasted as the end-product does not meet the expected outcome [66, 70]. The Product Development & Management Association (PDMA) best practice study found that product success rates are below 60% [37]. The striking price tag and failure rates often characterize prototyping as one of the largest sunk costs in product development [66]. One of the reasons that the prototyping process does not have a high success rate is due to its inherent complexities and uncertainties. According to the empirical results in the literature, different approaches and strategies of prototyping have a significant effect on the end product [216]. It is evident that prototyping plays a major role in product success and if it is not done systematically, companies lose significant resources. However, designers often rely on their experience and intuition while comes to prototyping [54].

Currently, there are no comprehensive, widely accepted, and easy to implement prototyping frameworks exist in the prototyping literature [54, 66, 144, 166]. The existing prototyping frameworks are largely prompt-based and rely on designers' experience and creativity to build a prototype [66, 144, 166]. Prompt-based activity and reliance on designers' creativity inject a variance in the quality of the prototype and resources used to create it [166].

Another deficiency of the current prototyping frameworks is inadequate consideration of Human Factor Engineering (HFE) principles while prototyping human-centered products [166]. The International Ergonomics Association define "Ergonomics (or human factors) as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design and optimize human well-being and overall system performance. Ergonomists contribute to the design and evaluation of tasks, jobs, products, environments, and systems to make design decisions compatible with the needs, abilities, and limitations of people" [11]. This definition clearly states that integrating the HFE theories and principles in the design of human-centered products improves human well-being and overall system performance. However, none of the existing prototyping frameworks integrates HFE, which leads to a lack of human factors considerations during the early phases of product design. Besides human well-being, another compelling reason to integrate HFE is that products that are designed by incorporating human factor guidelines tend to be more market successful than products that are not [201].

One of the challenges in considering HFE early in the design process is the lack of theoretical and practical knowledge on how to build prototypes to address ergonomics issues. Considering the limited resources available and tight schedules during the product conceptualization phase, collecting human-product interactions data becomes challenging [95]. Designers are often puzzled about how to proceed to execute ergonomic analyses due to the lack of comprehensive prototyping guidelines. Designers use either physical, computational, or mixed prototyping strategies to collect human-product interaction data [22]. However, each type of prototype has its own merits and demerits, and the effectiveness of the prototypes depends on the type of ergonomic assessment and the level of human-product interaction [19, 71, 252].

The limitations of the existing prototyping frameworks, particularly the inability to integrate HFE principles while prototyping human-centered products, is the driving motivation of this study. The limitations can be overcome by the Pre-Prototyping framework developed in Chapter 5. Therefore, Chapter 6 presents the same Pre-Prototyping framework developed in Chapter 5. However, the focus in this chapter is to extend the Pre-Prototyping framework by including a cost-benefit analysis to narrow down and select the final prototyping strategy. Further, this chapter focuses on analyzing the prototyping experience (qualitative analysis) of the participants who used the Pre-Prototyping framework, unlike Chapter 5 where the focus is on quantitative analysis.

6.3 Literature Review

6.3.1 Human Factor Engineering and Design Integration

Although HFE is theoretically positioned as one of the most crucial components of the product development processes, it is often not built in the early stages of prototyping and many times incorporated at the later phases of the design process [79,90,140]. A last-minute effort of integrating HFE design principles or taking corrective measures on functional prototypes or products in use is regarded as the reactive ergonomics approach [94, 118], which is usually associated with additional costs and time on product development. The traditional reactive approach has several limitations when it comes to ensuring ergonomics requirements at the later stages [27, 91]. First of all, the primary design decisions and resource allocations are already made; thus, the application of HFE design principles becomes much constrained and restricted, which creates design solutions that are sub-optimal from an ergonomics standpoint [31]. These sub-optimal solutions often reside in the system in the form of design deficiencies and poor human factors, which then lead to latent or catastrophic failures. Often the human operator gets blamed during an accident rather than the faulty designs [176]. Secondly, even if the changes are applied, the modifications enforced on the system architecture cause additional ergonomics problems. On the other hand, the proactive ergonomics approach suggests that ergonomics must be injected into products during the early design process to reduce or prevent human-product interaction issues preemptively (e.g., the risk of occupational injuries and discomfort) [196]. Thus, the proactive ergonomics approach provides a competitive edge to companies by creating products that potentially have better quality and enhanced usability [170]. The proactive ergonomics approach provides designers a better strategy in developing products that are improved in quality by overseeing human-product interactions as an essential part of the continuous improvement process, not a one-time event. Also, eliminating retrofitting and reactive ergonomics-related Interventions reduces the lead-time to market and require fewer resources [170].

6.3.2 Prototyping Frameworks

The concept of a prototyping framework is modified and leveraged from the works of Drezner and Camburn and is defined as a platform that can generate specific plans for building prototype [54,86]. A critical review of the recent prototyping literature shows that there are very few numbers of prototyping frameworks. Christie et al. (2012) proposed a prototyping framework that consists of nine prototyping factors, thirteen questions, and a prototyping strategy matrix. The strategy matrix allows visualization and organization of the results obtained from answering the thirteen questions. The strategy matrix helps designers to compare different prototyping concepts and selects the best concepts [66]. Camburn et al. (2015) developed a prototyping framework by integrating prototyping findings, best practices, and heuristics from prototyping literature. The framework is comprised of nine techniques and corresponding context variables and heuristics. It is a systematic framework that can be used to assess and weigh the techniques to calculate the best technique to build the prototype [54]. The study was validated against various prototyping activities performed by a controlled and Intervention group. It is found that the Intervention group developed better prototyping results compared to the Control group.

Menold et al. (2017) did an extensive literature review and identified three critical functions of prototypes, and derived four specifications. Their study proposed that any prototyping framework should meet the four specifications and also stated that, currently, no prototyping frameworks meet these four specifications. Thus, they developed a prototyping framework, named "The Prototype for X framework (PFX)", which is composed of three key phases: (1) Frame, (2) Build, and (3) Test. Further, Menold et al. introduced three lenses (feasibility, viability, and desirability) that designers can use to execute the three key phases systematically. These lenses are derived from Design-for-X and Human-Centered Design literature to integrate user-focused design into the framework [166]. Similar to other studies, Menold et al. also validated the framework by comparing prototyping activities between the control and Intervention (PFX) group. It is observed that, generally, the PFX group performed better than the Control group. One interesting observation is that within the PFX group, there is a variance in the quality of the prototype. Lauff et al. (2019) proposed a "Prototyping Canvas" which is a design tool to plan purposeful prototypes. Lauff et al. claim that often designers build prototypes without a clear purpose, and existing prototyping frameworks are challenging to implement in practice due to the lack of simple and useful design tools. Their Prototyping canvas is based on three prototyping principles, "Purpose, Resources, and Strategy", and the layout of the prototyping canvas is inspired by Business Model Canvas [144].

The literature review on the prototyping framework shows that there are only a few prototyping frameworks, and all of the studies claimed that current frameworks are not comprehensive and easy to implement. Additionally, none of the prototyping frameworks integrates HFE principles to prototype human-centered products. The existing frameworks reviewed here are questions and prompt-based, relying on the designer's creativity and experience to perform the activity. The prototyping frameworks are not specific and open-ended, which caused the designers and students to perform prototyping activities of high and low quality. For example, Menold's study showed that the Intervention (PFX) group came up with prototypes of high and low quality even though both groups followed the same prototyping framework [166]. One way to reduce this variance in quality is to develop a prototype framework that can give systematic and specific guidelines throughout the whole prototyping activity. None of the prototyping frameworks provided any fabrication or "know-how" guidelines on how to build the prototype. The "know-how" guidelines are important because the literature review shows that prototyping knowledge among the students and novice engineers are widely divergent [74, 166].

6.3.3 Human-Product Interactions and Type of Ergonomic Assessment

Interaction is defined as "A way of framing the relationship between people and objects designed for them and thus a way of framing the activity of design" [87]. Interaction between the operator and the workplace is a major factor that needs to be considered while designing a product or workplace to optimize human well-being and overall performance. Duffy et al. (2007) classified human-product interaction as a high- and low-level component. It is proposed in his study that the high-level human-product interaction should be assessed using physical prototypes, and low-level interaction should be assessed using computational prototypes [88]. This finding can be generalized as to use a high-fidelity prototype when assessing high-level human-product interaction and use a low-fidelity prototype when assessing low-level human-product interaction. This finding is confirmed by Ahmed et al. (2019), where three computational prototypes of different fidelity levels (high, mid, and low) are used to prototype two products that have high- and low-level human-product interactions, respectively. It is found that the product with low-level interaction can be assessed using all three prototypes. In other words, high, mid, and low-level fidelity prototypes can be used to assess low-level human-product interaction. However, the product with high-level human-product interaction can not be assessed using a low-fidelity prototype. The high-fidelity prototypes generate better results when compared to mid-level prototypes for assessing high-level human-product interactions [19].

Another factor that needs attention while building a prototype is the type of ergonomic assessment. Salvendy compiled and listed one hundred ergonomic factors, referred to as "The scope of HFE factors", in the Handbook of Human Factors and Ergonomics. These factors are also classified into seven categories [199]. It is out of the scope of this study to screen all the ergonomic factors, which are diverse and range from anthropometry and biomechanical to information flow and environmental factors. In practice, each of these factors requires numerous different strategies when used for ergonomics analyses. Hence, in this study, we focus on some of the common HFE factors that need to be considered while building prototypes.

6.4 Methodology

The literature review on the prototyping frameworks shows that all the previous studies use a similar methodology to create a knowledge base. The methodology starts with an extensive literature review followed by the distillation of the findings. The findings are distilled to identify the factors, questions, variables, heuristics, specifications, lenses, or key aspects that become the theoretical linchpin of the prototyping framework. For example, Christie et al. (2012) developed a "Prototype Strategy Matrix" from the factors and questions [66]. Camburn et al. (2015) proposed "Survey Tool" using the variables and heuristics [54]. Menold et al. (2017) introduced the "PFX" using specifications and lenses and Lauff et al. proposed "Prototyping Canvas" using key aspects [144, 166]. The methodology to

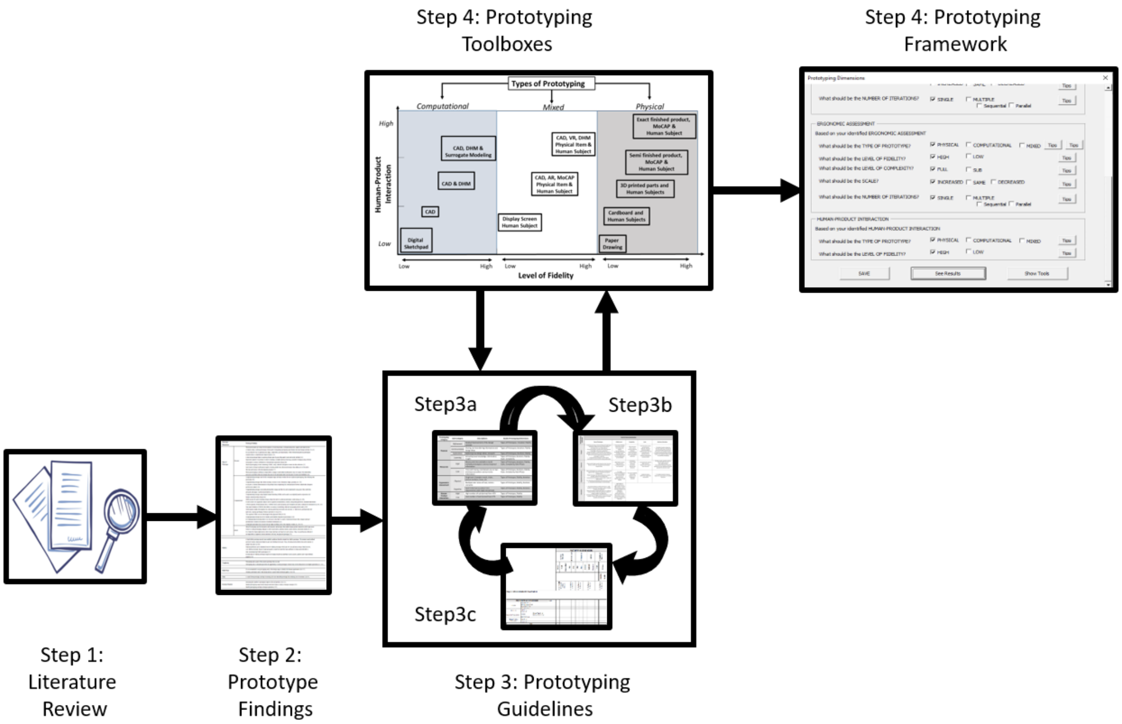


Figure 6.1: Methodology to create the prototyping framework

develop the prototyping framework in this study follows similar steps.

Figure 6.1 shows the steps to create the proposed prototyping framework. Step 1 is an extensive literature review on prototyping best practices and HFE guidelines. Note that due to space limitations, only a partial literature review is presented in Section 2. However, an enriched list of key findings from the literature review is summarized and presented in Table 6.1. Step 3 is the theoretical construct of the framework, which is inspired by the "House of Quality (HOQ)" [115]. HOQ is a product development tool that integrates "Customer Requirement" and "Engineering Requirements" to identify customer needs and how to achieve those needs,

Table 6.1: Step 2: Prototyping Findings

Prototype Dimensions		**Summary of Findings**	**References**
1.Type of Prototype	1.1. Physical	1.1.1. Provides exploration, refinement, learning, communication of ideas	[225] [47]
		1.1.2. Provides ergonomic assessment for multiple complex physical and/or cognitive task	[28]
		and high human-product interaction	[46]
		1.1.3. Provides tactile feedback	[40]
		1.1.4. Requires high resources, i.e. cost and time, less flexibility	[252]
	1.2. Computational	1.2.1. Facilitates communication and transfer of ideas	[51] [72]
		1.2.2. Facilitates learning and improvement early in the design process	[142] [184]
		1.2.3. For ergonomic assessment of single or few simple physical tasks for low human-product	[60]
		interaction, computational is preferable over physical	[51]
		1.2.4. Provides ergonomics assessment in a shorter time with less cost	[169]
		1.2.5. Provides ergonomic assessment where creating a physical prototype is infeasible	[111] [61]
		1.2.6. Multiple task analysis and Cognitive assessment is limited	[214] [89] [143]
	1.3. Mixed	1.3.1. Provides ergonomic assessment for moderate to simple physical and/or cognitive task	[25] [22]
		1.3.2. Limited tactile feedback	[36]
		1.3.3. It has some capabilities and limitations of both physical and computational prototype	[44] [36].
		1.3.4. Can be used where a physical prototype is infeasible or unsafe and computational prototype lacks fidelity	[25] [22] [55]
2. Fidelity	2.1. High	2.1.1. Provides accurate ergonomic assessment	[110]
		2.1.2. Provides feedback of finer details	[110]
		2.1.3. Requires more resources, i.e. cost and time	[110]
	2.2. Low	2.2.1. Provides rough ergonomic assessment	[46] [142]
		2.2.2. Provides limited tactile, auditory and visual feedback	[142]
		2.2.3. Requires less cost and time to build	[110] [237]
		2.2.4. Useful for creating quick multiple iterations, reducing design fixation and concept expression and exploration	[55] [215] [104]
3. Complexity	3.1. Sub-System	3.1.1. Requires fewer resources	[86]
		3.1.2. Provides in-depth exploration and focused ergonomic assessment only for a particular sub-system	[123], [66]
		3.1.3. Requires HTA to decide what sub-system to prototype	[16]
	3.2. Full System	3.2.1. Requires more resources	[86]
		3.2.2. Provides ergonomic assessment for the full system	[123] [66]
4. Scale	4.1. Full Scale	4.1.1. Create full scale prototypes if the budget allow	[66] [177]
	4.2. Altered	4.1.2. Create increased/decreased scale prototype for user evaluation	[66]
5. Iteration	5.1. Single	5.1.1. Provides a fewer number of feedback with less in-depth insight	[172] [85]
		5.1.2. Requires fewer resources	[172] [85]
	5.2. Multiple	5.2.1. Useful for refinement, gradual goal accomplishment, higher quality feedback, and the improved end product	[172] [85] [217]
		5.2.2. Parallel iteration useful for concept exploration	[84] [167]
		5.2.3. Quick iterations reduce design fixation	[229] [55]
		5.2.4. Cost of new information versus cost of iteration can guide the number of iterations	[215]

respectively. Similarly, Step 3a integrates “Prototyping Category” and “Prototyping Dimensions” to identify the needs of the prototype and how the prototype should be build so that it can achieve the needs, respectively. The “Prototyping Category”, “Prototyping Dimensions”, and their definitions are given in Tables 6.2 and 6.3. Step 3b is a matrix that connects “Prototyping Category” and “Prototyping Dimensions” via the prototyping findings and guidelines as derived from Table 6.1 as shows in Figure 6.2. The purpose of the matrix is to provide appro-

Table 6.2: Step 2: Prototyping Categories

Prototyping Category	**Sub-Category**	**Descriptions**
Purpose	Refinement	Gradual improvement of the design concept
	Communication	Sharing and transferring information and design ideas
	Exploration	Exploring new design ideas, concepts
	Learning	Extracting new knowledge, information, insight
Resources	High	Money and time available to build multiple prototypes to extract required information
	Low	Time and money constrained, one or two prototype possible to extract some information
Ergonomics Assessment	Physical	Single task: Examples reach, vision, posture analysis, stress, etc. Multiple task: Series of task, motion scenarios
	Cognitive	Multiple task: Series of task, motion scenarios
Human-Product Interaction	High	High number of task derived from HTA
	Low	Low number of task derived from HTA

Table 6.3: Step 2: Prototyping Dimensions

Prototyping Dimensions	**Sub-Dimensions**	**Descriptions**
Type of Prototype	Physical	It is the medium of prototype or how it is made. It can be either physical(cardboard, wood, etc.), computational (DHM, Sketchpad, etc.) and mixed (VR, AR, MoCap, etc.)
	Computational	
	Mixed	
Fidelity Level	High	It represents how accurately the prototype resembles the final product in terms of form, function, aesthetics
	Low	
Complexity	Full	The amount or portion of the product to be prototyped. For example, prototyping only the tip of the wing instead of the whole aircraft
	Sub	
Scale	Increased	It is the size of the prototype in terms of form and function to be prototyped
	Same	
	Decreased	
Number of Iterations	Single	It is about the number of the prototype to be created.
	Multiple	

priate guidelines that can be help designers to choose the correct “Prototyping Dimensions” for the “Prototyping Categories”. Step 3c represents the “House of Prototyping Guidelines (HOPG)”, which is the final step of the theoretical construct. HOPG connects Step 3a and Step 3b within a single platform that can

PROTOTYPING CATEGORIES	PROTOTYPING DIMENSIONS				
	Type of Prototypes (Physical/Mixed/Computational)	***Fidelity Level***	***Complexity***	***Scale***	***Number of iterations***
Purpose	• If refining, learning, communicating and exploring is adequately addressed using computational prototype than use computational • Physical prototype is preferred for extracting new knowledge, refinement, exploration • Mixed prototype is preferred when the product is digitally created however, tactile and other feed back which can not be created using computational prototype is required • Computational prototype is preferred for international communication among stakeholders	• If any level of fidelity satisfy the purpose then choose low fidelity • For learning new knowledge of function, use high fidelity • For quick ideation and concept exploration use low fidelity	• If the functions, forms can be learned, explored, refined or communicated by only a sub system then sub system is preferred	• If the functions, forms can be learned, explored, refined or communicated by unaltered scale, then use unaltered scale. • Altered scale can enhances learning and communication	• If multiple iterations improves learning, exploring, refining and communicating of functions and forms then use multiple iterations • If parallel prototyping reduces design fixation and improves ideation then use parallel prototyping
Resources	• Physical prototype usually requires most resources (finance, time), mixed prototype in between and computational prototypes requires least (keeping fidelity constant)	• High fidelity requires high resources • Low fidelity requires less resources	• Full System requires high resources • Sub system requires less resources	• Increased scale requires high resources • Reduce scale requires less resources	• Multiple and/or parallel iterations requires high resources than single iteration • Use multiple iterations if benefits gained from each additional iteration exceeds the resources used
Ergonomics Assessment	• Physical Prototype can usually assess all physical and cognitive from single to multiple and simple to complex task • Mixed Prototype can assess moderately simple to complex physical and complex task • Computational Prototype is preferred for single and physical task • For infeasible and hazardous task assessment, mixed or computational prototype is recommended	• For single, unconstrained physical task use low fidelity • For a sequence of physical and/or cognitive task use high fidelity • High fidelity provides more accurate ergonomics assessment than low fidelity	• Use sub complexity if the whole product is not designed or assessed	• Unaltered scale is preferred in ergonomic assessment	• If multiple iteration improves ergonomic assessment use multiple iterations
Interaction	• Physical Prototype is preferred if there is a high number of task in HTA and high number of design variables and objectives • Mixed Prototype is preferred if there is a moderate number of task in HTA and moderate number of design variables and objectives • Computational Prototype is preferred if there is a low number of task in HTA and low number of design variables and objectives	• High Fidelity is preferred if there is high number of task in HTA and high number of design variables and objectives • Low fidelity is preferred if there is low number of task in HTA and low number of design variables and objectives			

Figure 6.2: The Matrix of Prototyping Categories and Dimensions

be used to rate the "Prototyping Categories" and "Prototyping Dimensions", and select the final "Prototyping Dimensions". Figure 6.4(a) shows the HOPG, which can be used by designers to rate the "Prototyping Categories" based on the given "Prototyping Problem Statement". Next, based on the guidelines provided in the "Matrix", designers can rate the "Prototyping Dimensions". The value of the "Prototyping Dimensions" is calculated using the following equation. Designers can select the "Prototyping Dimensions", which has the highest sum.

$$
\begin{aligned}
Sum &= Weight \times Rate \qquad (6.1)\\
Weight &= \text{prototyping categories}\\
Rate &= \text{prototyping dimensions}
\end{aligned}
$$

Step 4 brings the practical "know-how" guidelines into the prototyping framework. The motivation for providing "know-how" guidelines in the framework comes from the lack of standard and consistent prototyping practices. Christie et al. (2012), Deininger et al. (2017), and Menold et al. (2017) reported in their studies that design students and novice designers have inaccurate, incomplete, and varied perceptions of prototyping activities [66, 74, 166]. Thus, it is one of the many reasons why there is a significant difference in the quality of the prototypes among designers who use the same prototyping tools. Hence, a framework that only provides theoretical guidelines is insufficient to warrant a consistent and high-quality prototyping activity. Fabrication guidelines, in the form of prototyping "know-how", should be integrated with the theoretical guidelines to develop a systematic and holistic framework.

The practical guidelines of prototyping activities are integrated into the framework via "Prototyping Toolbox", which is a glossary of tools that are often used in hands-on prototyping activities and organized based on three axes, as shown in Figure 6.3: (1) Human-Product Interaction, (2) Fidelity Level, and (3) Types of Prototypes. These axes are leveraged from the works of Stowe (2008) and Duffy

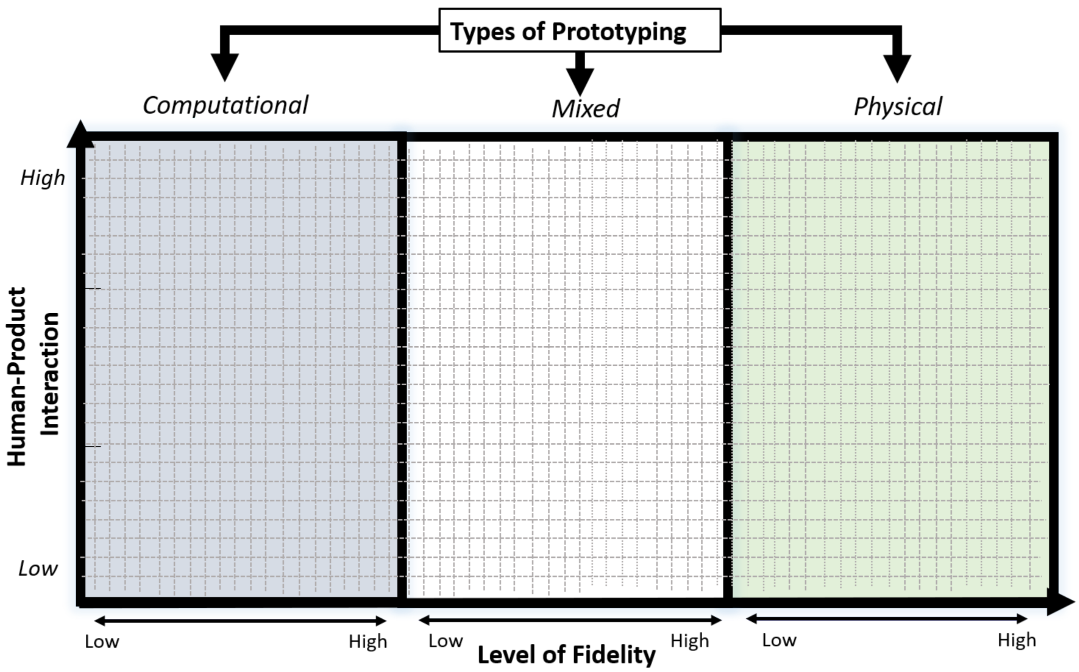


Figure 6.3: The Prototyping Toolbox

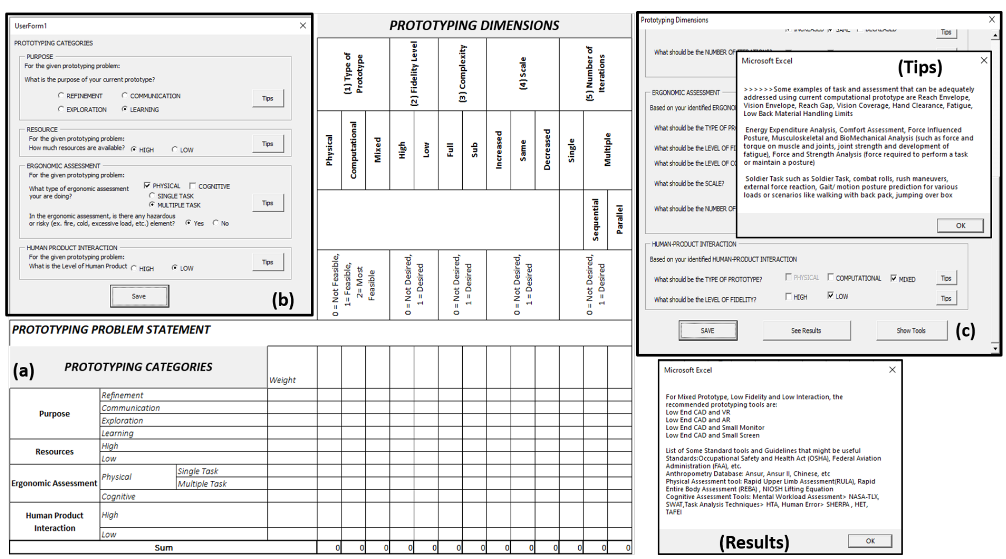


Figure 6.4: The Prototyping Framework

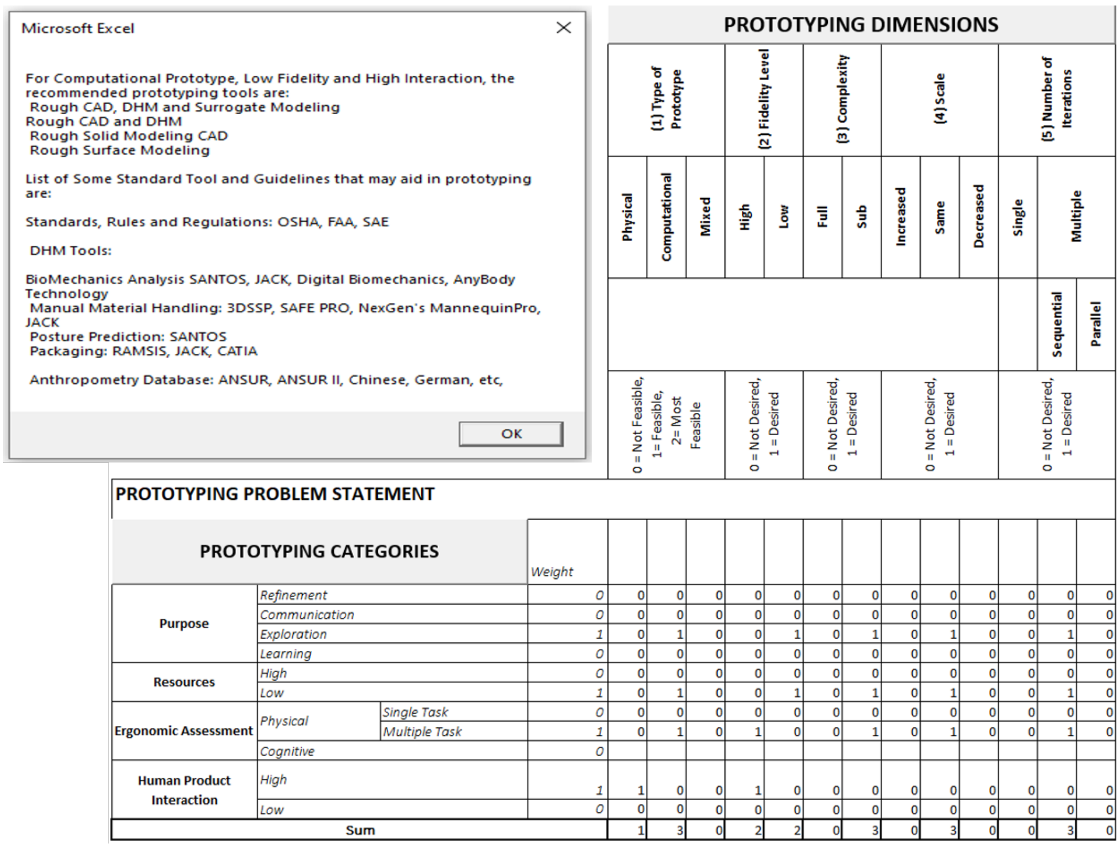
(2007) [88, 212] and help us to represent prototyping activities collectively. The "Human-Product Interaction and Fidelity Level" are considered to be continuum since human-product interaction and fidelity can be any level; however, "Types of Prototypes" is considered discrete and of three types. To use this toolbox, first, the designer needs to organize and fill up the box with the resources (tools and technologies) that are available. In Step 3, the "Human-Product Interaction, Fidelity Level, and Types of Prototypes" are calculated using HOPG. Using the values of "Human-Product Interaction, Fidelity Level, and Types of Prototypes", as identified in Step 3, designers can navigate the toolbox and identify the appropriate tools and technologies that can be used to create the prototype.

In Step 5, the core results from the previous steps are combined, and the final framework is presented using MS Excel User-Form to provide a graphical interface where the HOPG, the Matrix of Prototyping Categories and Dimensions, and the Toolbox are integrated. Figure 6.4 shows a snippet of the prototyping framework. The designer starts by understanding the given prototyping problem and by selecting the "Prototyping Categories". As the "Prototyping Categories" button is clicked, a new pop-up window emerges (Figure 6.4(b)) where the designer can select the appropriate categories. To aid the designer, definitions of the terms and appropriate guidelines related to the "Prototyping Categories" are integrated into the form of "Tips", and the pop-up window shows appropriate tips. Next, the designer clicks the "Prototyping Dimensions" button and a new pop-up window emerges (Figure 6.4c). As the designer goes through the "Prototyping Categories and Prototyping Dimensions", the HOPG gets populated, and the values are calculated using Equation 1 as shown (Figure 6.4(a)). Finally, the designer can see the prototyping strategy by clicking the "Show Tools" button, which pulls up a new window showing the identified prototyping dimensions and the relevant tools needed to build the prototype.

6.5 Prototyping Activity Cost-Benefit Analysis

Prototyping can become a sunk cost if it is not performed efficiently [37,66,70,231]. Often there are multiple ways to build a prototype to obtain information or satisfy design objectives. The existing prototyping frameworks offer various strategies to build prototypes, and not all of them are of equal value. Hence, it is important to identify prototyping strategies that are efficient and holds the most value before any significant investments are made. In this study, the value of prototyping activity is based on Camburn et al.'s (2017) and Tiong (2019) et al.'s work, where the value of prototyping activity is defined as the information gained from the prototype with respect to resources spent to build it [55, 218].

In this study, the value of a prototype is considered to be a function of the information obtained from the prototyping activity and the resources spent to achieve it. The information gained from a prototype is defined as the product of the amount of information and the accuracy or fidelity of the information. The fidelity of the information is quantified by comparing the accuracy of the information from the prototype to the accuracy of the information obtained from the final product or the ideal product [152]. Therefore, the value of the fidelity should range between



PROTOTYPING DIMENSIONS				(1) Type of Prototype			(2) Fidelity Level		(3) Complexity		(4) Scale			(5) Number of Iterations		
				Physical	Computational	Mixed	High	Low	Full	Sub	Increased	Same	Decreased	Single	Multiple	
															Sequential	Parallel
				0 = Not Feasible, 1= Feasible, 2= Most Feasible			0 = Not Desired, 1 = Desired		0 = Not Desired, 1 = Desired		0 = Not Desired, 1 = Desired			0 = Not Desired, 1 = Desired		
PROTOTYPING PROBLEM STATEMENT																
PROTOTYPING CATEGORIES			Weight													
Purpose	Refinement		0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Communication		0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Exploration		1	0	1	0	0	1	0	1	0	1	0	0	1	0
	Learning		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Resources	High		0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Low		1	0	1	0	0	1	0	1	0	1	0	0	1	0
Ergonomic Assessment	Physical	Single Task	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Multiple Task	1	0	1	0	1	0	0	1	0	1	0	0	1	0
	Cognitive		0													
Human Product Interaction	High		1	1	0	0	1	0	0	0	0	0	0	0	0	0
	Low		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum				1	3	0	2	2	0	3	0	3	0	0	3	0

Figure 6.5: Prototyping Strategy for the Ergonomic Analysis and Design of a Cockpit

0 to 1. The concept of resources spend or the cost of prototyping is leveraged from the Engineering Design book by Pahl and Beitz [178]. The total cost of prototyping can be divided into material cost, product cost, and administrative cost. Each of these three costs is further broken down into direct and indirect cost, but it is not shown here in detail due to space limitations. So, with the above-mentioned concept of “Information Gained” and “Cost”, the value of prototyping can be formulated as follows:

$$
\begin{aligned}
V &\propto f(I, C) && (6.2)\\
I &= I_n \times F && (6.3)\\
C &= C_M + C_P + C_A && (6.4)\\
V &= \frac{I}{C} && (6.5)\\
V &= \frac{I_n \times F}{C_M + C_P + C_A}
\end{aligned}
$$

$$V = Value,\ I = Information,\ C = Cost$$

$$I_n = Amount\ of\ Information,\ F = Fidelity\ of\ Information$$

$$C_M = Material,\ C_P = Production,\ C_A = Administrative\ Cost$$

6.6 Case Study

In this section, a prototyping problem adapted from our previous prototyping research work (ergonomic analysis and design for the occupant packaging of a cockpit) [19] is used as a case study to demonstrate the usability and efficacy of the framework. The study starts with the prototyping problem statements, and then a walk-through is provided, followed by a cost-benefit analysis. The goal of the case study is to show how the framework can be used in the concept design phase. Due to space limitations, only a snippet of the prototyping work is provided in this paper to illustrate how the prototyping framework functions. The following paragraph illustrates the high-level prototyping problem statement:

You are to conceptualize a prototyping strategy to redesign a civilian cockpit to improve the pilot's reaching and vision performance during landing an aircraft. During an aircraft landing, the pilot visually confirms the taxiway through the windshield and reaches flap switches and landing gear switches in the instrument panel. You can adjust the orientation of the instrument panel and pilot seat to enhance vision and reach performance. You are given low resources.

The problem statement provides important clues on what is expected out of the prototype. Once the designer launches the MS Excel User-Form, each phase of the prototyping framework offers different guidelines and prototyping best practices, and additional information can be accessed through the "Tips" box. These tips can guide the designer which "Prototyping Categories and Prototyping Dimensions" to select and ultimately derive the prototyping strategy to build. Thus, the designer can select and deselect different categories on the MS Excel User-Form based on the prototyping problem statement.

The second step is to identify the appropriate "Prototyping Categories" for the prototyping problem and "Tips". The first "Prototyping Category" is "Purpose" as shown in Figure 6.4(a). The "Tips" corresponding to "Purpose" show that "Exploration and Learning" both are appropriate to create a new design and gain new knowledge. Hence, "Exploration" is selected. Next "Prototyping Category" is "Resources", and it is given in the prototyping problem statement the low resources are provided. Thus, "Low" option is chosen. Next, the designer selects the appropriate "Ergonomic Assessment" based on the problem statement. In the above example, the pilot is working on a physical task such as reaching and visualizing; therefore, "Physical" option is chosen. Also, "Multiple Task" options is selected since the pilot is working on a landing task that requires multiple task execution, including looking at the taxi, reaching flaps, and landing gears. Finally, within the "Human Product Interaction" area, "High" option is chosen because the pilot is interacting with multiple objects, and there are multiple design variables such as the orientation of the instrument panel and seat distance. After selecting all the appropriate "Prototyping Categories", the designer should "Save" and close the window. The "Weight" column is now automatically generated, reflecting the designer's choices, as shown in Figure 6.5.

In the third step, the designer identifies the appropriate "Prototyping Dimensions" based on the previously identified "Prototyping Categories" and the embedded prototyping best practices given in the "Tips". The first "Prototyping Dimension" is "Type of Prototype", and based on the "Purpose, Resources and Ergonomics Assessment" and the the "Tips", "Computational Prototype" is selected. It is because "Computational Prototype" can be used to explore the design; in general, it needs lower resources than the mixed and physical prototype. Additionally, according to the provided guidelines, the ergonomic assessment of reach and vision can be done using the computational prototype. However, based on "Human-Product Interaction", "Physical Prototype" is preferred because the "Tips" indicates high “Physical Prototype” is more suitable for prototyping “Human-Product Interaction”. The second “Prototyping Dimension” is “Level of Fidelity” and the general “Tips” for fidelity is to use low-level fidelity if the “Purpose” is to quick concept ideation and exploration. For “Resource” category, the “Tips” is that high-level fidelity is more resource-intensive than low-level fidelity. So, “Low Level Fidelity” is selected for “Purpose and Resource”. However, for “Ergonomic Assessment and Human-Product Interaction”, “High Level Fidelity” is selected. The “Tips” here is to use a high-level of fidelity since there is a series of tasks (reach and vision) and multiple human-product interactions (reaching flaps, landing gear, multiple design variables). For “Level of Complexity” category, “Sub Level” is selected as the “Tips” are to choose “Sub” over “Full” if only a partial prototype is sufficient to test the “Purpose”, the “Resource” is low, and only if part of the product is tested. Similarly, for “Scale” category, “Same” is selected because in human-centered product design practices using the same scale is coded into the MS Excel User-Form by the ideal practice when “Resource” is low. Finally, for “Number of Iteration” category, “Multiple Sequential” is chosen because the “Tips” for this selection suggest that it can help to explore the design space and improve ergonomics assessment when it comes to “Purpose and Ergonomic Assessment”. However, “Single” iterations is chosen with respect to “Resource” since multiple iteration is resource-intensive. Once all the “Prototyping Dimensions” are selected, then the designer can “Save” the MS Excel User-Form, and the HOPG gets populated automatically. Finally, the designer can check the “Result” and “Tools” to see the suggested prototyping strategy. Figure 6.5 shows the populated HOPG and the prototyping strategy to build the prototype.

Figure 6.5 shows several tools within a computational prototyping toolbox (Fig. 6.3) such as "Rough Computer-Aided Design (CAD) model, Digital Human Modeling (DHM) simulation, and Surrogate modeling" and "Rough CAD and DHM" in decreasing order of fidelity. Each of these prototyping tools has various ranges of capacity to do the required prototyping. A designer can perform a cost-benefit analysis to calculate which prototyping tool holds the maximum value. For illustration purposes, an estimated cost-benefit analysis between the "Rough CAD, DHM, and Surrogate modeling" and "Rough CAD and DHM" is presented here. For example, within the "Rough CAD and DHM" option, software packages such as SolidWorks for CAD modeling and Jack Siemens for DHM simulation are required. Within the "Rough CAD, DHM, and Surrogate modeling" option, one may require MATLAB software package for Surrogate Modeling, in addition to the SolidWorks and Jack Siemens. For the sake of simplicity, let us assume two scenarios: (1) the cost of computational resources and hourly designer salaries are the same except that "Rough CAD, DHM, and Surrogate modeling" is more time consuming than "Rough CAD and DHM", and (2) the amount of information retrieved from these two prototypes is the same, but the fidelity of the information is different. For example, say that "Rough CAD, DHM, and Surrogate modeling" option is associated with 0.9 fidelity level and 4 hours of design work and "Rough CAD and DHM" has 0.5 fidelity and 3 hours, both with a designer hourly salary rate of \$15/hr. The cost-benefit analysis is as follows:

For "Rough CAD, DHM and Surrogate modeling":

$$V = \frac{I_n \times F}{C} = \frac{I_n \times 0.9}{15 \times 4} = 0.015 I_n$$

For "Rough CAD and DHM":

$$V = \frac{I_n \times F}{C} = \frac{I_n \times 0.5}{15 \times 3} = 0.011 I_n$$

This quick-and-dirty cost-benefit analysis shows that even though the "Rough CAD, DHM and Surrogate modeling" is costlier than "Rough CAD and DHM" but it has more value.

Table 6.4: Intervention Group Likert Scale Data

Questions	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
1. I have heard about prototyping/created prototype before and knowledgeable about it	3	5	0	0	1
2. I have known ergonomics/human factors/ human centered design concept before	3	5	1	0	0
3. I understood the given prototyping problem	3	6	0	0	0
4. I understood the MS Excel User-Form and was able to use it correctly	1	7	1	0	0
5. The MS Excel User-Form helped in taking prototyping decisions	1	8	0	0	0
6. The MS Excel User-Form helped me to consider some factors which I might not have thought independently	4	4	1	0	0
7. The MS Excel User-Form helped me to built a better prototype than I would have independently	5	3	1	0	0
8. An inexperienced designer might do better prototyping using the framework instead of only relying on intuition	5	3	1	0	0

6.7 Validation of the Conceptual Prototyping Framework

The conceptual Prototyping Framework is validated by comparing the prototyping strategies developed between the Intervention group and Control group. Eighteen

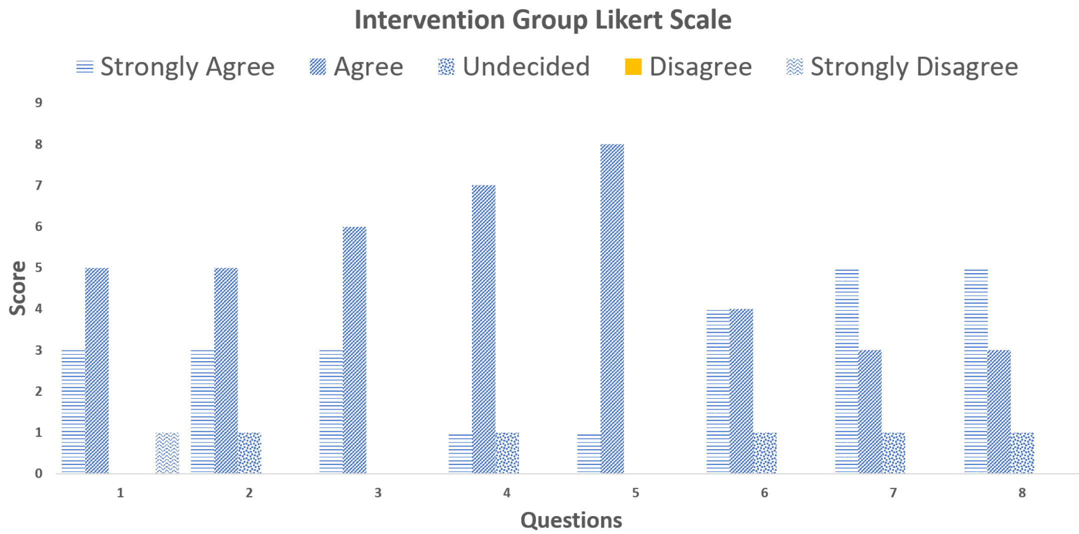


Figure 6.6: Intervention Group Likert Scale

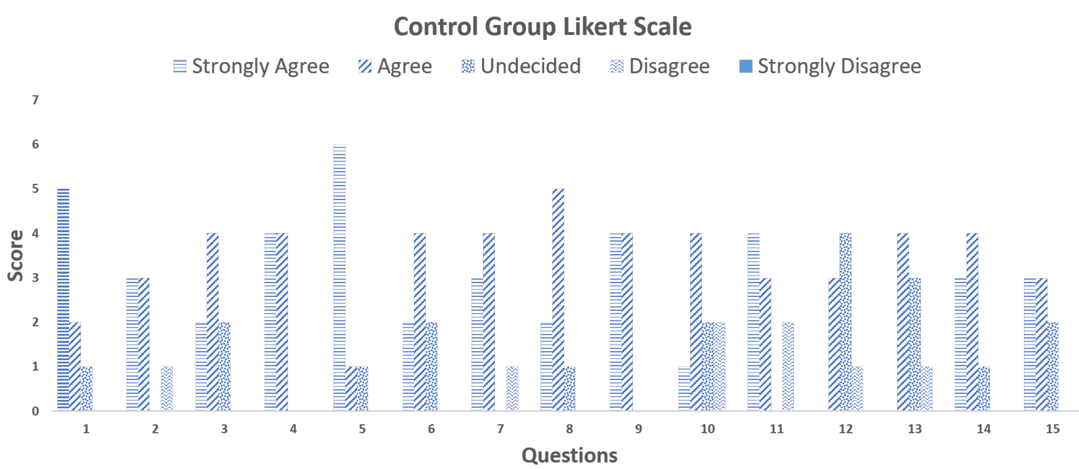


Figure 6.7: Control group Likert Scale

participants participated in the experiment, and they were randomly divided either into the Intervention or Control group. Both groups are given the same twelve prototyping problems, and their Prototyping Score is measured using equation 5.2

Table 6.5: Control group Likert Scale Data

Questions	**Strongly Agree**	**Agree**	**Undecided**	**Disagree**	**Strongly Disagree**
1. I have heard about prototyping/ created prototype before and knowledgeable about it	5	2	1	0	0
2. I have known ergonomics/human factor/ human centered design concept before	3	3	0	1	0
3. I understood the given prototyping problem	2	4	2	0	0
4. I have considered about the "purpose of the prototype" while developing the prototype	4	4	0	0	0
5. I have considered about the "resource availability" while developing the prototype	6	1	1	0	0
6. I have considered about the "type of ergonomic assessment" while developing the prototype	2	4	2	0	0
7. I have considered about the "human-product interaction" while developing the prototype	3	4	0	1	0
8. I have considered about the "type of prototype (physical, computational or mixed)" while developing the prototype	2	5	1	0	0
9. I have considered about the "level of fidelity" while developing the prototype	4	4	0	0	0
10. I have considered about the "scaling (big, same or small size)" while developing the prototype	1	4	2	2	0
11. I have considered about the "complexity (create in full or partly)" while developing the prototype	4	3	0	2	0
12. I have considered about the "number of iterations" while developing the prototype	0	3	4	1	0
13. I have considered all the prototyping factors stated in questions 4 to 12 while developing the prototype	0	4	3	1	0
14. If I have known or considered all the prototyping factors then I might have developed a better prototype	3	4	1	0	0
15. If I have used the MS Excel User-Form then I might have created a better prototype	3	3	2	0	0

as shown in Section 5.6. The Prototyping Score is statistically analyzed using independent samples t-test to identify whether there is a significant difference in the Prototyping Score of the two groups. The details of the statistical test and analysis are given in Chapter 5. In addition to measuring the Prototyping Score, their prototyping experience is captured through a five-point Likert Scale test and via screen recording. In this chapter, the analysis of the prototyping experience of the participants from both groups is focused on. Both groups were given various questions related to their prototyping activity to capture their experience and attitude through the Likert Scale. The Likert Scale questionnaire and its result are shown in Tables 6.4 and 6.5. The prototyping experience is also captured by recording the screen while the participants took the test. The screen recording shows how the Intervention groups followed the given Tutorials, examples and how well the participants got acquainted with the MS Excel User-Form and the number of times they read the Tips. Reading the given Instructions, going through the Tutorial, examples, and Tips are considered as the Preparation Time before taking the prototyping experiments. The Preparation Time and Number of Tips Read are measured from the screen recording video and tabulated against Prototyping Score in Tables 6.9 and 6.10.

6.8 Results and Discussion

A novel prototyping framework is proposed in this paper to addresses the research gap of integrating HFE into the prototyping activity. Another significant contribution is the inclusion of the technology toolbox, which complements the theoretical prototyping best-practices so that designers have guidelines from the fabrication (including modeling and simulation) point of view. Combining the theoretical guidelines and practical toolbox can help designers build a prototype based on proven best practices rather than just relying on self-creativity. A systematic and holistic framework, where both the theory and practice of prototyping are integrated, can further help to reduce the reliance on self-creativity or design bias.

Additionally, a cost-benefit analysis is added to this conceptual prototyping framework. To narrow down the potential best prototyping strategy, the cost-benefit analysis can be used to calculate the "Value" of the prototype, which is essentially a function of information gained over the expense of the resources used.

A case study adapted from previously published prototyping work is used to demonstrate the usability and effectiveness of the prototyping framework [19]. The prototyping framework is used to generate strategies for ergonomic analysis of a concept cockpit from an occupant packaging perspective. Figure 6.5 shows the tabulated HOPG in MS Excel User-Form and the recommended prototyping strategies. The "Weight" column shows the value of the "Prototyping Categories" as selected by the designer based on the problem statements and the "Tips". A value of 1 indicates that it has been selected, and 0 is otherwise. The "Sum" row shows the final calculated value for each "Prototyping Dimensions". The "Prototyping Dimensions" with the highest value are deemed to be the most feasible one. A summary of the prototyping strategy reflecting the most viable "Prototyping Dimensions" and the corresponding tools to build the prototype is shown in the message box. The recommended theoretical prototyping strategy, "Prototyping Dimensions", are computational prototype, low-level fidelity, sub-complexity, same scale, and multiple sequential iterations. The tools and technologies needed to build the prototype for the identified theoretical strategy are "Rough CAD, DHM, and Surrogate Modeling", "Rough CAD and DHM", "Rough CAD", etc. A list of tools in the order of decreasing fidelity is provided because, more often than not, there are multiple ways to prototype a product. Providing a list of tools and guidelines ensures that all viable strategies are explored. The designer can narrow down the tools by doing a comparative cost-benefit analysis to find out which prototyping tools hold the most value. A resource-intensive prototype may have a higher value than a less resource-intensive one or vice versa. In this case study, the surrogate modeling approach provides more value ($0.015\mathrm{I_n}$) than that of the only CAD and DHM ($0.011\mathrm{I_n}$).

The independent sample t-test showed that the Prototyping Score of the Intervention group is significantly higher than that of the Control group. More about the analysis of the t-test is given in Section 5.9. In addition to the statistical validation of the conceptual prototyping framework, the prototyping experience of the participants is captured to understand their prototyping activity. The first four questions given to the Intervention group in Table 6.4 are designed to understand how knowledgeable the participants are about prototyping, ergonomics, given prototyping problem, and the MS User Excel Form. The following four questions are designed to comprehend the precipitant's experience regarding the conceptual prototyping framework. Figure 6.6 shows that a hundred percent of participants either strongly agree or just agree to question five, i.e., the conceptual prototyping framework helped them to create prototyping strategies. Similarly, it also shows that the majority of the participants either strongly agree or just agree that the conceptual prototyping framework helped them to build a better prototype than they would have independently, and they agree that the conceptual prototyping framework is useful for designers who are familiar with prototyping and human-centered design.

Similarly, the Control group's experience is captured using the questionnaire as shown in Table 6.5. The Control group are given different sets of the question compared to Intervention group because the Control group did not get the MS User-Form. The first three questions deal with their understanding of prototyping and human factors. It can be seen that the majority of the participants from both the group are aware of the prototyping and human-factors. Next, the Control group is asked whether they are aware of the prototyping factors such as *purpose, resource, type of ergonomic assessment, level of fidelity, etc.* as can be seen from questions four to twelve. Figure 6.7 shows that the majority of the participants from the Control group are aware of these prototyping factors and human factors. However, even though the Control group is familiar with these factors, which are the building block of the conceptual prototyping framework, the Control group's prototyping score is significantly lower than that of the Intervention group. The contradiction of knowing the prototyping factors and human factors and scoring a low prototyping score, i.e., developing inadequate prototyping strategy by the Control group can be reconciled if it is assumed that the Control group lacked a deep understanding of the factors. The Control group was simply aware or had a superficial understanding of the prototyping factors and the human factors. The Intervention group not only got to know about these factors through the conceptual prototyping framework but they also got to know about the guidelines and best practices regarding these factors. These guidelines and best practices in the form of "Tips" helped the Intervention group to gain a deep understanding regarding these factors. Additionally, the MS Excel User-Form is streamlined such that it adapts based on the participant's input and narrows down possible prototyping strategies by filtering out or opting out that prototyping factor and human factors which are not suitable for that particular prototyping problem. The prototyping factors, human factors guidelines, best practices, and streamlined MS User Excel set the Intervention group apart from the Control group and thus giving the Intervention group an advantage in developing better prototyping strategies. Further, the Control group was given a chance to use the MS Excel form after they finished developing the twelve prototyping strategies. As question fifteen shows the majority of the Control group agrees that they might have developed better prototyping strategies if they were given the conceptual prototyping framework, i.e., the MS Excel User-Form earlier.

Table 6.6: Intervention Group Average Prototyping Score Per Question

Questions	1	2	3	4	5	6	7	8	9	10	11	12
Average prototyping Score	3.889	2.222	3.778	3.333	3.333	3.444	3.222	3.444	3.222	3.556	3.333	3.889

Table 6.7: Control group Average Prototyping Score Per Question

Questions	1	2	3	4	5	6	7	8	9	10	11	12
Average prototyping Score	2.556	2.333	2.667	1.556	3.444	3.444	2.222	2.333	3.444	2.444	3.111	3.778

Some interesting observations are seen by comparing the average prototyping score per question between the Intervention group and Control group as shown in Tables 6.6 and 6.7 and Figures 6.8 and 6.9. Figures 6.8 and 6.9 show that the average prototyping score of the Intervention group is consistent, whereas the average prototyping score of the Control group varies wildly. Table 6.8 shows that

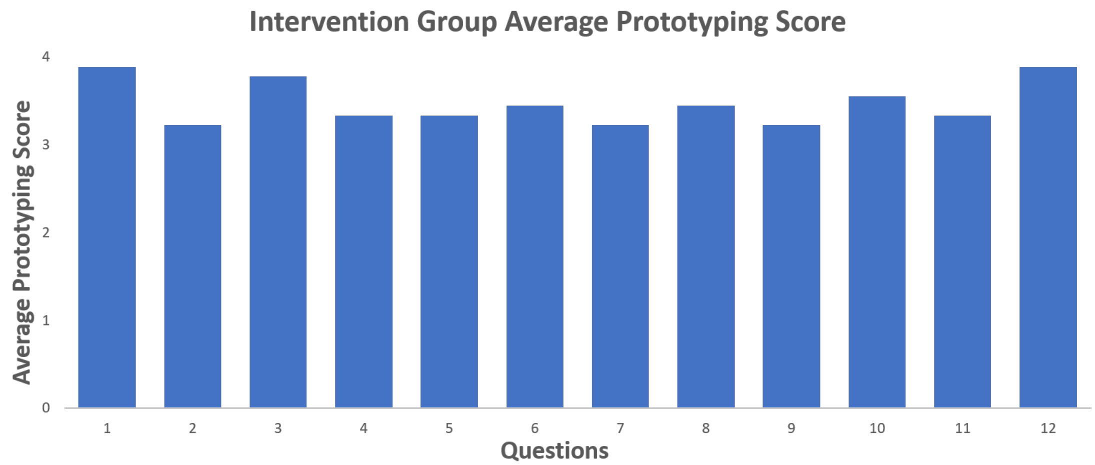


Figure 6.8: Intervention Group Average Prototyping Score Per Question

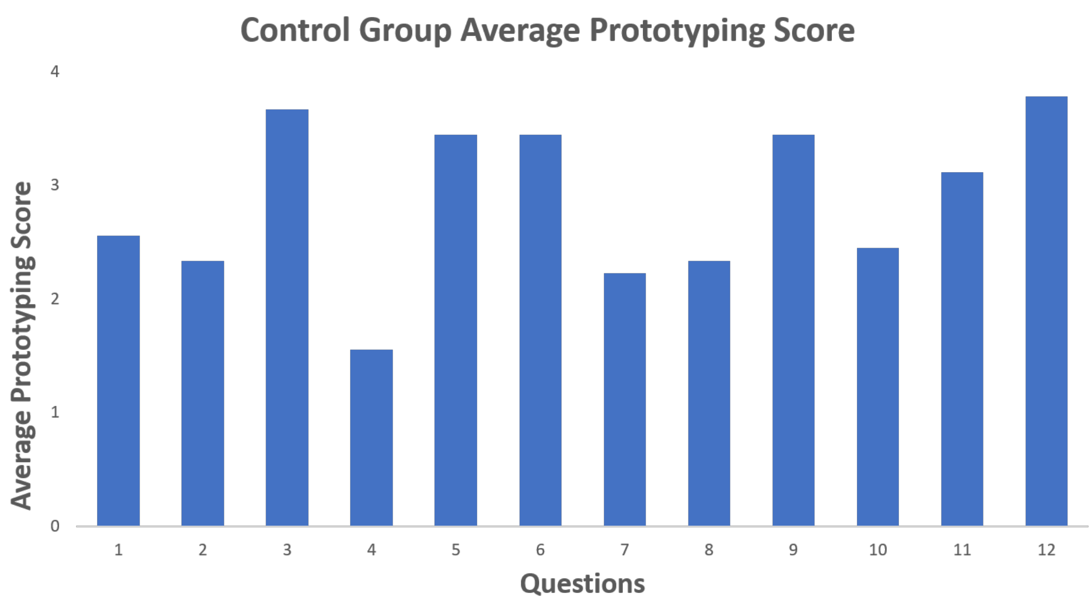


Figure 6.9: Control group Average Prototyping Score Per Question

the standard deviation and as well as the range of the prototyping score of the Control group is much higher (around three times) than that of the Intervention

Table 6.8: Comparison of Average Prototyping Score Per Question Between Two Groups

	Standard Deviation	**Minimum Value**	**Maximum Value**	**Range**
Intervention Group Per Question Average Prototyping Score	0.251	3.222	3.889	0.667
Control group Per Question Average Prototyping Score	0.708	1.556	3.778	2.222

group. This observation can be attributed that the Intervention group had the conceptual prototyping framework and the streamlined MS Excel User-Form which guided and assisted them to develop the correct prototyping framework. However, the Control group participants were not guided. Hence, they randomly created prototyping strategies based on their intuition and thus the quality and correctness of the prototyping strategies varied a lot.

Table 6.9: Preparation time versus Prototyping Score of Intervention Group Participants

Participants	1	2	3	4	5	6
Preparation Time (minutes)	13	2	31	18	68	25
Average Prototyping Score Per Participants	3.33	3.33	3.67	2.90	3.90	3.83
Pearson Correlation, r	0.66					

Table 6.10: Total Tips Read versus Prototyping Score of Intervention Group Participants

Participants	1	2	3	4	5	6
Number of Tips Read	8	35	25	10	33	35
Average Prototyping Score Per Participants	3.33	3.33	3.67	2.90	3.90	3.83
Pearson Correlation, r	0.71					

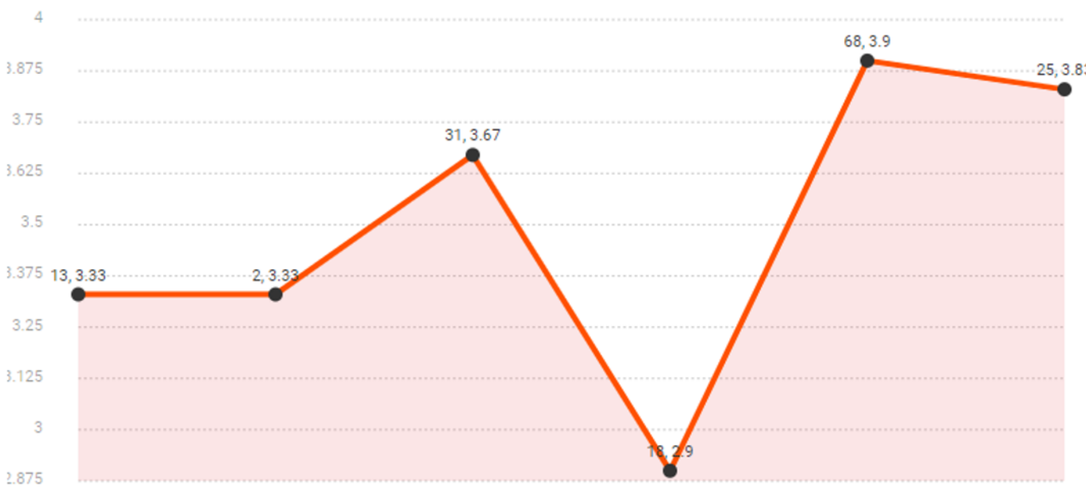


Figure 6.10: Preparation Time versus Prototyping Score

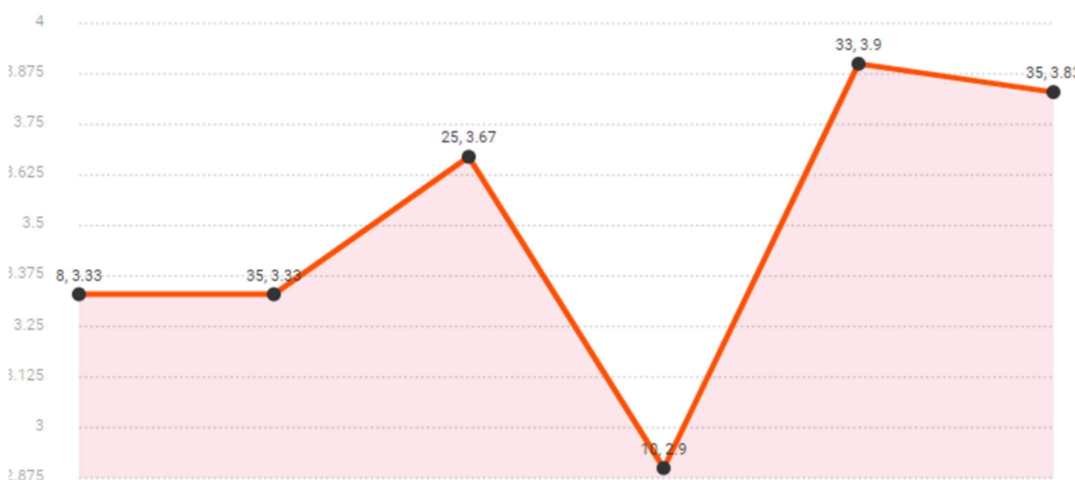


Figure 6.11: Total Tips Read versus Prototyping Score

Another expected observation regarding the Preparation Time and the Number of Tips Read by the Intervention group versus the corresponding prototyping score is made as shown in Tables 6.9 and 6.10 and Figures 6.10 and 6.11, respectively. It is expected that the participants who spent more time familiarizing the tutorials, examples, Tips, MS Excel User-Form will perform better than those who do not. A positive Pearson correlation of 0.66 and 0.71 is found for Preparation Time versus prototyping score and the Number of Tips Read versus prototyping score, respectively.

The prototyping framework presented in this study can help designers in providing theoretical and fabrication guidelines to develop prototypes for human-centered products. The statistical analysis in Chapter 5 and the prototyping experience analysis done in this chapter suggest that the conceptual prototyping framework guides and assists designers in developing better prototyping strategies than those designers who rely on their intuition. The overall idea is to assist designers who are not well-versed in the human factor and ergonomics. Though every effort has been made to make the prototyping framework as comprehensive as possible, due to the inherent complexity of prototyping, a designer should use the prototyping framework only for assistance and not for the lead. The prototyping framework will output better results if it is coupled with the designer's expertise and judgment. It is developed to guide and direct the prototyping activities in the right direction before the hands-on prototyping activity starts.

6.9 Limitations and Future Work

The proposed prototyping framework has several limitations. The limitations of the Pre-Prototyping framework are mentioned in Chapter 5. In this section, the limitation of the cost-benefit analysis and the Pre-Prototyping framework validation experiment is discussed. In the cost-benefit analysis, the value of the prototype is defined as proportional to the information over cost. The information is quantified as a product of the amount of information and its fidelity. It is difficult to quantify the amount of information extracted from prototypes and it is also difficult to equate the information obtained from different prototypes. For example, in a cost-benefit analysis between Prototype 1 and 2, "X" and "Y" amount of information is gained from prototype 1 and 2 respectively. it is difficult to say whether "X" is equal to "Y" or half of "Y", etc. The quantification becomes subjective and depends on the designer's expertise and experience. Similarly, the fidelity of the information is difficult to measure too. To measure the fidelity of the prototype, the information obtained from the prototype needs to be compared to the information from the actual product or a very good model/prototype. For example, to measure the fidelity of a computational model, it needs to be compared to the actual physical model. Hence, quantifying the fidelity becomes resource-intensive.

The Pre-Prototyping experiment had a limited number of participants. Though the statistical test and prototyping experiences observed between the Intervention and Control are significantly different, a larger number of participants would have improved the scope of inference. Further study on cost-benefit analysis on how to quantify the information and fidelity of the prototype would be an interesting avenue of future research. Additionally, future studies with a larger number of participants would improve the scope of inference of the statistical test and would also reveal more prototyping experiences from the participants.

Chapter 7: Conclusion

7.1 Research Contribution

This dissertation's overall research goal and contribution is the development of a Pre-Prototyping framework for human-centered products. The primary reason for developing the Pre-Prototyping framework is the lack of systematic methodologies and guidelines in the literature that focuses specifically on human-centered products. The research work presented in this dissertation fills up this gap by developing a framework that integrates the prototyping guidelines and best practices with the HFE principles. The framework provides prototyping strategies, including theoretical and fabrication guidelines for designers who want to design human-centered products by integrating human factors and ergonomics. The Pre-Prototyping framework can be used during the early stages of the design process to assist designers in making decisions regarding prototyping strategies that can help save valuable product development resources and ultimately aid in developing quality products.

During the literature survey, it is found that there is not a sufficient amount of prototyping findings, prototyping best practices, and human-factors guidelines related to human-centered products exists that enable designers to develop a prototyping framework. Hence, some research avenues such as human-product interaction level and prototyping findings related to various PSFs are explored to gain and create knowledge. These research avenues directly contributed to developing the Pre-Prototyping framework.

Several research questions and hypotheses are formulated in this dissertation, which helped explore the research avenues and develop the Pre-Prototyping framework. The following is a brief description of how each research question and hypothesis were answered and validated.

- **SRQ 1.** What type of prototype (computational or mixed) should be used to capture the effect of Performance Shaping Factors (PSFs) (fire and smoke) on human performance (posture and vision)?

  - **SRH 1.** Mixed prototype is better in capturing human performance than that of computational prototype due to PSFs.

This hypothesis is validated in Chapter 2 by comparing the mixed prototyping and computational prototyping approach to simulate a pilot's performance during an emergency. It is presented in Tables 2.1 and 2.2 that computational prototype (CAD and DHM) is insufficient to simulate the pilot's vision and posture analysis during a fire and smoke emergency in the cockpit. In contrast, the mixed prototype (VR, MoCAP, Human Subject) can be used to simulate to assess ergonomics during emergencies.

- **SRQ 2.** How can we use digital human modeling (DHM) tools to create a surrogate model and explore the design space for human-centered products?

- **SRH 2.** The proposed computational prototype using CAD, DHM, and surrogate modeling explores a larger design space than computational prototypes which uses only CAD and DHM.

This hypothesis is addressed in Chapter 3 by developing a design process (Figure 3.2) that can integrate human factors and as well as explore a large design space. The proposed design process uses HTA to decide which tasks to be used during the simulation setup. Then CAD and DHM are used to create and simulate the workplace and human interaction. The surrogate modeling technique is used to mathematically model the "what-if" human-product interaction, and the optimization technique is used to explore the design space.

- **SRQ 3.** How does the human-product interaction level, prototyping fidelity level, and type of ergonomics analysis affect the prototyping strategies of human-centered products?

  - **SRH 3.** Higher human-product interaction products should be prototyped using higher fidelity prototypes.

This hypothesis is addressed in Chapter 4 by exploring different levels of human-product interaction and the types of ergonomics assessment using three prototypes with low-, mid-, and high-level of fidelity. This study is about understanding the relation among human-product interactions, the fidelity level of prototypes, and ergonomics analysis of the task and how they can be taken into account during developing prototyping strategies. It is found that low-level human-product interaction can be prototyped using both low- and high-fidelity level prototypes.

However, high-level human-product interaction can only be prototyped using a high fidelity level prototype.

- **PRQ 1.** *What prototyping findings (best practices) and guidelines should be used for prototyping human-centered product?*
  - **PRH 1.** Designers who use the proposed theoretical prototyping guidelines will conceptualize better prototypes than those designers who do not.

This hypothesis is addressed in Chapters 5 and 6 by identifying the necessary theories required to build a prototype. The prototyping theory consists of the critical prototyping factors and guidelines related to the human-centered product design. Table 2 in Appendix A, Figures 1 in Appendix B, 5.2, 5.3 and 5.4 presents the required prototyping factors and corresponding guidelines for prototyping human-centered products. These prototyping factors are extracted from the prototyping and human-factors literature. The prototyping factors are divided into Prototyping Categories and Prototyping Dimensions. Prototyping Categories are used to identify the purpose and requirement that the prototype should fulfill. Furthermore, the Prototyping Dimensions is used to identify the specification or configuration of the prototype that can fulfill the requirement. The validation study showed that the Intervention group who used the proposed prototyping guidelines developed better prototyping strategies than that of the Control group.

- **PRQ 2.** *What prototyping tools and technologies should be used to create for prototyping human-centered product?*

- **PRH 2.** Designers who use the proposed prototyping toolbox will conceptualize better prototypes than those designers who do not.

This hypothesis is addressed in Chapters 5 and 6. In this hypothesis, prototyping fabrication guidelines are captured. Hypothesis 5 is the counterpart of Hypothesis 4, as Hypothesis 4 presents the theoretical part, whereas Hypothesis 5 presents the practical part, i.e., fabrication guidelines. Figure 5.6 presents the Prototyping Toolbox. The toolbox has three axes: Human-Product Interaction Level, Level of Fidelity of prototypes, and Types of Prototyping. These three axes are used to organize the tools. The prototyping theories, i.e., prototyping factors from Hypothesis 4, are used as a guide to navigating the Prototyping Toolbox. The validation study showed that the Intervention group who used the proposed prototyping toolbox developed better prototyping strategies than that of the Control group.

- **PRQ 3.** What is the methodology to develop the Pre-Prototyping framework for HCD based products?

  - **PRH 3**. Designers who use the proposed prototyping framework will conceptualize better prototypes than those designers who do not.

The last hypothesis is also covered in Chapters 5 and 6. In this hypothesis, a Pre-Prototyping framework is developed by combining the outcomes from Hypotheses 4 and 5, i.e., prototyping theories (factors and guidelines) and the practicals (Prototyping Toolbox). The Pre-Prototyping framework is based on MS Excel

User-Form. The User-Form helps to streamline the prototyping theories and prototyping practicals so that a designer can systematically use the Pre-Prototyping framework. The framework presents guidelines (theoretical and practical) relevant to the prototyping problem at hand so that the designer can make better prototyping strategies and decisions related to human-centered products. The validation study showed that the Intervention group that used the proposed Pre-Prototyping framework developed better prototyping strategies than the Control group.

Here is a list of the journal (J) and conference (C) publications related to the six hypotheses.

- **SRH 1**
  - **J1.** Ahmed, S., & Onan Demirel, H. (2020). A Framework to Assess Human Performance in Normal and Emergency Situations. ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg, 6(1). https://doi.org/10.1115/1.4044791
  - **C1.** Ahmed, S., Zhang, J., & Demirel, O. (2018, July). Assessment of types of prototyping in human-centered product design. In International Conference on Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management (pp. 3-18). Springer, Cham. https://doi.org/10.1007/978-3-319-91397-1_1
- **SRH 2**
  - **J2.** Ahmed, S., Irshad, L., Gawand, M. S., & Demirel, H. O. (2021).

Integrating human factors early in the design process using digital human modelling and surrogate modelling. Journal of Engineering Design, 32(4), 165-186.
https://doi.org/10.1080/09544828.2020.1869704

- **C2.** Ahmed, S., Gawand, M. S., Irshad, L., & Demirel, H. O. (2018, August). Exploring the design space using a surrogate model approach with digital human modeling simulations. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (Vol. 51739, p. V01BT02A011). American Society of Mechanical Engineers
https://doi.org/10.1115/DETC2018-86323

- **SRH 3**

  - **J3.** Ahmed, S., Irshad, L., & Demirel, H. O. (2021). Prototyping Human-Centered Products in the Age of Industry 4.0. Journal of Mechanical Design, 143(7), 071102.
https://doi.org/10.1115/1.4050736

  - **C3.** Ahmed, S., Irshad, L., & Demirel, H. O. (2019, August). Computational Prototyping Methods to Design Human Centered Products of High and Low Level Human Interactions. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (Vol. 59278, p. V007T06A047). American Society of Mechanical Engineers.

https://doi.org/10.1115/DETC2019-98450

- **C4.** Ahmed, S., Irshad, L., Demirel, H. O., & Tumer, I. Y. (2019, July). A comparison between virtual reality and digital human modeling for proactive ergonomic design. In International Conference on Human-Computer Interaction (pp. 3-21). Springer, Cham. https://doi.org/10.1007/978-3-030-22216-1_1

- **PRH 1, PRH 2 and PRH 3**

  - **C5.** Ahmed, S., & Demirel, H. O. (2020, July). House of Prototyping Guidelines: A Framework to Develop Theoretical Prototyping Strategies for Human-Centered Design. In International Conference on Human-Computer Interaction (pp. 21-38). Springer, Cham. https://doi.org/10.1007/978-3-030-49713-2_2

  - **C6.** Ahmed, S., & Demirel, H. O. (2020, August). A Pre-Prototyping framework to Explore Human-Centered Prototyping Strategies During Early Design. In ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/DETC2020-22700

  - **C7.** Ahmed, S., & Demirel, H. O. (2020, November). A Conceptual Prototyping Framework for Integrating Human Factors Early in Product Design. In ASME International Mechanical Engineering Congress and Exposition (Vol. 84539, p. V006T06A023). American Society of

Mechanical Engineers.
https://doi.org/10.1115/IMECE2020-23858

- **C8.** Ahmed, S., & Demirel, H. O. (2021). A Prototyping Framework for Human-Centered Product Design: Preliminary Validation Study. In International Conference on Human-Computer Interaction. Springer, Cham. (Accepted)
- **J4.** Ahmed, S., & Demirel, H. O. (2021). A Pre-Prototyping framework to Explore Human-Centered Prototyping Strategies During Early Design. (To be submitted)
- **J5.** Ahmed, S., & Demirel, H. O. (2021). A Conceptual Prototyping Framework for Integrating Human Factors Early in Product Design. (To be submitted)

- **Other Publications During Ph.D. Time**
  - **C9.** Ahmed, S., Demirel, H. O., Tumer, I. Y., & Stone, R. B. (2018). Towards human-induced failure assessment during early design. Tools and Methods of Competitive Engineering (TMCE 2018), Las Palmas de Gran Canaria, Spain, May, 7-11.
  - **J6.** Irshad, L., Ahmed, S., Demirel, H. O., & Tumer, I. Y. (2019). Computational functional failure analysis to identify human errors during early design stages. Journal of Computing and Information Science in Engineering, 19(3).
  https://doi.org/10.1115/1.4042697

- **J7.** Demirel, H. O., Ahmed, S., & Duffy, V. G. (2021). Digital Human Modeling: A Review and Reappraisal of Origins, Present, and Expected Future Methods for Representing Humans Computationally. International Journal of Human-Computer Interaction. (Accepted under review)
- **C10.** Irshad, L., Ahmed, S., Demirel, O., & Tumer, I. Y. (2018, August). Identification of human errors during early design stage functional failure analysis. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (Vol. 51739, p. V01BT02A007). American Society of Mechanical Engineers.
  https://doi.org/10.1115/DETC2018-8597
- **C12.** Irshad, L., Ahmed, S., Demirel, O., & Tumer, I. Y. (2019). Coupling digital human modeling with early design stage human error analysis to assess ergonomic vulnerabilities. In AIAA Scitech 2019 Forum (p. 2349).
  https://doi.org/10.2514/6.2019-2349
- **C13.** & Demirel, H. O., Irshad, L., Ahmed, S.,(2021). Digital Human-in-the-loop Methodology for Early Design Computational Human Factors. In International Conference on Human-Computer Interaction. Springer, Cham. (Accepted)

Table 7.1 summarizes the hypothesis, research contributions and the corresponding publications.

Table 7.1: Summary of Research Contributions and Publications

Hypothesis	**Section**	**Contribution**	**Area of Contributions**	**Publications**
Secondary Research Hypothesis (SRH) 1	2.5.2, 2.6.2 2.7	Prototyping findings related to PSF and Type of Prototype	Prototyping, Human Factors	J1 and C1
Secondary Research Hypothesis (SRH) 2	3.4, 3.5	A design technique to integrate human factors and explore the design space	Prototyping, Human Factors Design Process	J2 and C2
Secondary Research Hypothesis (SRH) 3	4.4, 4.5 4.6	Prototyping findings related to human-product interaction, type of ergonomic assessment and prototype fidelity level	Prototyping, Human Factors Design Process	J3, C3 and C4
Primary Research Hypothesis (PRH) 1	5.4.2, 5.7, 5.8, 6.4 6.7	Prototyping theories, critical factors related human-centered products	Prototyping, Human Factors Design Process	C5, C6, C7 C8, J4 and J5
Primary Research Hypothesis (PRH) 2	5.4.3, 5.7 5.8, 6.4 6.7	Prototyping fabrication guidelines related human-centered products	Prototyping, Human Factors Design Process	
Primary Research Hypothesis (PRH) 3	5.4, 5.7 5.8, 6.4, 6.7	The Pre-Prototyping Framework to prototype human-centered products	Prototyping, Human Factors Design Process	

7.2 Limitations

The Pre-Prototyping framework developed in this dissertation has several limitations. One of the limitations is some of the prototyping theories that are integrated into the framework are not specific enough. This limitation occurs due to the scarcity of prototyping findings related to human-centered products. Though the broadness of the prototyping theories improves the generalization of the framework, it might show limitations if there is a human-centered prototyping problem with a unique ergonomic assessment and human-product interaction level.

The prototyping toolbox presented in this work is partially filled with tools and technologies that can be used for fabrication prototypes. However, due to the ever-changing tools and technologies present in the market, it is not possible to make a comprehensive toolbox. Additionally, the type of tools to be used depends on the expertise of the designer and the availability of resources which makes it improbable and infeasible to create the comprehensive prototyping toolbox.

Another limitation is that the designers need to go through a learning curve to effectively use the Pre-Prototyping framework. The designers need to get familiarized with how the Pre-Prototyping framework interface works by reading tips, tutorials, examples, etc. The learning curve is around twenty to thirty minutes, making it less appealing to designers who want to develop prototype strategies quickly.

7.3 Future Work

Various future endeavors can be taken to improve the work presented in this dissertation. The future works are divided by their research area and presented here.

7.3.1 Prototyping Findings related to Human-Centered Products

The prototyping literature related to human-centered products by considering the ergonomics and human factors is scarce. The literature does not provide adequate guidelines on how to develop prototyping strategies by considering the human element in the product or workplace. Whenever there is a human in the picture, the Performance Shaping Factors, human-product interaction level, type of ergonomics assessment, safety, physical and cognitive interactions, etc., need to be taken into account while building a prototype. There are insufficient prototyping guidelines that can account for the above-mentioned human factors. It is because the prototyping findings related to these human factors are not well studied. These studies need to be conducted to gain a deeper understanding of these prototyping findings related to human-centered products. The resulting prototyping findings can help to improve the Pre-Prototyping framework by enriching the tips, guidelines, prototyping toolbox, etc.

7.3.2 Domain Specific Pre-Prototyping framework

As much as it is needed to generalize and broaden the scope of the Pre-Prototyping framework, it is also equally, if not more important to develop a domain-specific Pre-Prototyping framework. Medical devices, sports products, automobiles, airplanes, space stations, furniture, home appliances, assembly lines, manufacturing tools, and main other products or systems have human involvement. Though the element "human involvement" is common in all the aforementioned products and workplaces, however, the type and level of human-product interaction are different and unique. Whereas a generalized version Pre-Prototyping framework might provide some level of prototyping strategies for these products, a domain-specific Pre-Prototyping framework is desirable and beneficial. For example, reach, vision and comfort analyses might be sufficient for occupant packaging studies in the automobile domain; however, an assembly line that involves workers picking heavy loads in awkward postures need upper and lower body lifting force assessments. Similarly, medical devices like surgical tools might not be heavy and do not need significant lifting force, but they might require pinching, gripping, fine finger movement analysis. Hence, products and workplaces across different domains have different human-product interactions and different ergonomics assessments. Thus, the prototyping strategies are also going to be different. Hence, developing a domain-specific Pre-Prototyping framework by integrating the domain-specific knowledge will be beneficial.

7.3.3 Automated Pre-Prototyping framework

One interesting avenue of future research is to make the Pre-Prototyping framework automated, i.e., eliminating the need to have a designer go step by step over the Pre-Prototyping framework to develop prototyping strategies. It can be achieved by making the Pre-Prototyping framework smarter by integrating artificial intelligence (AI). The AI will read and comprehend the prototyping problem and then go through the prototyping theories, best practices, and fabrication guidelines integrated into the framework to generate the required prototyping strategies. This automated approach has the advantage of reducing time, designer cost, and biases. However, there might be a disadvantage of not having the designer's expertise and experience if the process gets automated by eliminating the designer.

7.3.4 CAD Integration

Another interesting and exciting research avenue is to integrate the Pre-Prototyping framework in the design process. Currently, the Pre-Prototyping framework is a standalone platform, i.e., designers generate concepts in another platform and then use the Pre-Prototyping framework to develop prototyping strategies on how they test their generated concepts. Seamless integration between the concept generation platform and the Pre-Prototyping framework will enable the designers to generate concepts and also develop prototyping strategies simultaneously. This seamless integration will make the whole design process quicker and efficient.

The next level of future work would be to integrate the automation as discussed in Section 7.3.3 with the concept generation and Pre-Prototyping framework platform. This seamless integration of concept generation, Pre-Prototyping framework with automation will allow designers to automatically and instantly verify whether the generated concepts can be prototyped and tested. This feature will help designers to decide if their concept is feasible or not and eliminate infeasible concepts.

Bibliography

[1] Emergency — definition of emergency in english by oxford dictionaries. https://en.oxforddictionaries.com/definition/emergency. (Accessed on 11/30/2018).

[2] Exclusive: Us-bangla pilot was mentally stressed and reckless - national - the kathmandu post. http://kathmandupost.ekantipur.com/news/2018-08-27/exclusive-us-bangla-pilot-was-mentally-stressed-and-reckless.html. (Accessed on 11/29/2018).

[3] How a faulty heater caused the windshield in the cockpit of a passenger jet to shatter - thousands of feet above the atlantic — daily mail online. https://www.dailymail.co.uk/news/article-1290535/How-faulty-heater-caused-windshield-cockpit-passenger-jet-shatter--thousands-feet-Atlantic.html. (Accessed on 11/25/2018).

[4] Improving medication safety. Technical report, World Health Organization.

[5] Incidents, events involving boeing cockpit fires - the san diego union-tribune. https://www.sandiegouniontribune.com/sdut-incidents-events-involving-boeing-cockpit-fires-2010jun29-story.html. (Accessed on 11/25/2018).

[6] Jack. https://www.plm.automation.siemens.com/store/en-us/jack/. (Accessed on 11/25/2018).

[7] Simlab cloud showroom. http://www.simlab-soft.com/technologies/simlab-showroom.aspx. (Accessed on 11/25/2018).

[8] Sketchpad 5.1 - draw, create, share! https://sketch.io/sketchpad/. (Accessed on 02/23/2019).

[9] Us-bangla airlines flight crash: Guilty, who? — the daily star. https://www.thedailystar.net/frontpage/us-bangla-airlines-flight-crash-guilty-who-1547413. (Accessed on 11/24/2018).

[10] Wayback machine. https://web.archive.org/web/20180416020057/http://www.tourism.gov.np/downloadfile/DRAFT%20PRELIMINARY%20REPORT%20FOR%20COMMISSION_1523376481.pdf. (Accessed on 11/16/2018).

[11] What is ergonomics? — the international ergonomics association is a global federation of human factors/ergonomics societies, registered as a nonprofit organization in geneva, switzerland. https://iea.cc/what-is-ergonomics/#:~:text=Ergonomics%20(or%20human%20factors)%20is,being%20and%20overall%20system%20performance. (Accessed on 05/31/2021).

[12] The industry of the future - france in the united kingdom - la france au royaume-uni. https://uk.ambafrance.org/The-Industry-of-the-Future, 2020. (Accessed on 08/29/2020).

[13] "made in china 2025" industrial policies: Issues for congress. https://fas.org/sgp/crs/row/IF10964.pdf, 2020. (Accessed on 08/29/2020).

[14] Karim Abdel-Malek, Jasbir Arora, Rajan Bhatt, Kimberly Farrell, Chris Murphy, and Kevin Kregel. Santos. In Sofia Scataglini and Gunther Paul, editors, *DHM and Posturography*, pages 63–77. Elsevier, 2019.

[15] M. J. Ackerman. The visible human project(r): From body to bits. *Conf Proc IEEE Eng Med Biol Soc*, 2016:3338–3341, 2016.

[16] Salman Ahmed, Mihir Sunil Gawand, Lukman Irshad, and H. Onan Demirel. Exploring the design space using a surrogate model approach with digital human modeling simulations. In *ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages V01BT02A011–V01BT02A011. American Society of Mechanical Engineers, 2018.

[17] Salman Ahmed, Chung-Hyun Goh, Janet K Allen, Farrokh Mistree, Pramod Zagade, and BP Gautham. Hot forging of automobile steel gear blanks: An exploration of the solution space. In *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages V02BT03A003–V02BT03A003. American Society of Mechanical Engineers, 2014.

[18] Salman Ahmed, Chung-hyun Goh, B P Gautham, Pramod Zagade, Janet K Allen, and Farrokh Mistree. Design Space Exploration with the Preemptive and Archimedean Formulations of the Compromise Decision Support Problem. 15(1):1–16, 2014.

[19] Salman Ahmed, Lukman Irshad, and H. Onan Demirel. Computational prototyping methods to design human centered products of high and low level human interactions. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 59278, page V007T06A047. American Society of Mechanical Engineers, 2019.

[20] Salman Ahmed, Lukman Irshad, and H. Onan Demirel. Prototyping human-centered products in the age of industry 4.0. *Journal of Mechanical Design*, 143(7), 2021.

[21] Salman Ahmed, Lukman Irshad, H. Onan Demirel, and Irem Y. Tumer. A comparison between virtual reality and digital human modeling for proactive ergonomic design. In V. G. Duffy, editor, *International Conference on Human-Computer Interaction*, volume Lecture Notes in Computer Science: Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Human Body and Motion, pages 3–21, Cham, 2019. Springer International Publishing.

[22] Salman Ahmed, Lukman Irshad, H. Onan Demirel, and Irem Y Tumer. A comparison between virtual reality and digital human modeling for proactive ergonomic design. In *International Conference on Human-Computer Interaction*, pages 3–21. Springer, 2019.

[23] Salman Ahmed, Lukman Irshad, Mihir Sunil Gawand, and H. Onan Demirel. Integrating human factors early in the design process using digital human modelling and surrogate modelling. *Journal of Engineering Design*, pages 1–22, 2021.

[24] Salman Ahmed and H Onan Demirel. A framework to assess human performance in normal and emergency situations. *ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg*, 6(1), 2020.

[25] Salman Ahmed, Jianfu Zhang, and Onan Demirel. Assessment of types of prototyping in human-centered product design. In *International Conference*

on Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management, pages 3–18. Springer, 2018.

[26] A Alaswad, AG Olabi, and KY Benyounis. Integration of finite element analysis and design of experiments to analyse the geometrical factors in bi-layered tube hydroforming. *Materials & Design*, 32(2):838–850, 2011.

[27] D Alexander. The cost justification process, auburn engineers. *Inc, Auburn, Alabama*, 1999.

[28] Kosmas Alexopoulos, Dimitris Mavrikios, and George Chryssolouris. Ergo-toolkit: an ergonomic analysis tool in a virtual manufacturing environment. *International Journal of Computer Integrated Manufacturing*, 26(5):440–452, 2013.

[29] Francisco Almada-Lobo. The industry 4.0 revolution and the future of manufacturing execution systems (mes). *Journal of innovation management*, 3(4):16–21, 2015.

[30] René Amalberti. *La conduite de systèmes à risques: le travail à l'hôpital*. Presses universitaires de France, 1996.

[31] DJ Andrews. Simulation and the design building block approach in the design of ships and other complex systems. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 462(2075):3407–3433, 2006.

[32] Stephen J Andriole. *Storyboard prototyping: a new approach to user requirements analysis*. QED Information Sciences Inc., Wellesley, 1989.

[33] Susanna Aromaa and Kaisa Väänänen. Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design. *Applied ergonomics*, 56:11–18, 2016.

[34] Charles Audet, J Denni, Douglas Moore, Andrew Booker, and Paul Frank. A surrogate-model-based method for constrained optimization. In *8th Symposium on Multidisciplinary Analysis and Optimization*, page 4891, 2000.

[35] Radu F Babiceanu and Remzi Seker. Big data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook. *Computers in Industry*, 81:128–137, 2016.

[36] Loris Barbieri, Agostino Angilica, Fabio Bruno, and Maurizio Muzzupappa. Mixed prototyping with configurable physical archetype for usability evaluation of product interfaces. *Computers in Industry*, 64(3):310–323, 2013.

[37] Gloria Barczak, Abbie Griffin, and Kenneth B Kahn. Perspective: trends and drivers of success in npd practices: results of the 2003 pdma best practices study. *Journal of product innovation management*, 26(1):3–23, 2009.

[38] Christoph Jan Bartodziej. The concept industry 4.0. In *The concept industry 4.0*, pages 27–50. Springer, 2017.

[39] David Beevis and Gaetan St Denis. Rapid prototyping and the human factors engineering process. *Applied ergonomics*, 23(3):155–160, 1992.

[40] ZM Bi. Computer integrated reconfigurable experimental platform for ergonomic study of vehicle body design. *International Journal of Computer Integrated Manufacturing*, 23(11):968–978, 2010.

[41] Michael Binnard. *Design by composition for rapid prototyping*, volume 525. Springer Science & Business Media, 2012.

[42] Peter Blanchonette. Jack human modelling tool: A review. Technical report, DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION VICTORIA (AUSTRALIA) AIR . . . , 2010.

[43] Chase Boothe, Lesley Strawderman, and Ethan Hosea. The effects of prototype medium on usability testing. *Applied ergonomics*, 44(6):1033–1038, 2013.

[44] Monica Bordegoni, Umberto Cugini, Giandomenico Caruso, and Samuele Polistina. Mixed prototyping for product assessment: a reference framework. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 3(3):177–187, 2009.

[45] Monica Bordegoni and Caterina Rizzi. *Innovation in product design: from CAD to virtual prototyping*. Springer, 2011.

[46] Margot Brereton and Ben McGarry. An observational study of how objects support engineering design thinking and communication: implications for the design of tangible media. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, pages 217–224. ACM, 2000.

[47] Johan J Broek, Wouter Sleijffers, Imre Horváth, and Alex F Lennings. Using physical models in design. In *Proceedings of CAID/CD'2000 conference*, pages 155–163, 2000.

[48] Erik Brolin, Dan Högberg, and Pernilla Nurbo. Statistical posture prediction of vehicle occupants in digital human modelling tools. In *International Conference on Human-Computer Interaction*, pages 3–17. Springer, 2020.

[49] Heiner Bubb. Why do we need digital human models? In Sofia Scataglini and Gunther Paul, editors, *DHM and Posturography*, pages 7–32. Elsevier, London, 2019.

[50] Heiner Bubb, Florian Engstler, Florian Fritzsche, Christian Mergl, Olaf Sabbah, Peter Schaefer, and Iris Zacher. The development of ramsis in past and future as an example for the cooperation between industry and university. *International Journal of Human Factors Modelling and Simulation*, 1(1):140–157, 2006.

[51] HANS-JÖRG BULLINGER and Manfred Dangelmaier. Virtual prototyping and testing of in-vehicle interfaces. *Ergonomics*, 46(1-3):41–51, 2003.

[52] Barbara K Burian and Immanuel Barshi. Emergency and abnormal situations: A review of asrs reports. In *Proceedings of the 12th International Symposium on Aviation Psychology. Wright State University Press, Dayton, Ohio*, 2003.

[53] Barbara K Burian, Immanuel Barshi, and Key Dismukes. The challenge of aviation emergency and abnormal situations. 2005.

[54] Bradley Camburn, Brock Dunlap, Tanmay Gurjar, Christopher Hamon, Matthew Green, Daniel Jensen, Richard Crawford, Kevin Otto, and Kristin Wood. A systematic method for design prototyping. *Journal of Mechanical Design*, 137(8):081102, 2015.

[55] Bradley Camburn, Vimal Viswanathan, Julie Linsey, David Anderson, Daniel Jensen, Richard Crawford, Kevin Otto, and Kristin Wood. Design prototyping methods: state of the art in strategies, techniques, and guidelines. *Design Science*, 3, 2017.

[56] F. Caputo, A. Greco, M. Fera, and R. Macchiaroli. Workplace design ergonomic validation based on multiple human factors assessment methods and simulation. *Production & Manufacturing Research*, 7(1):195–222, 2019.

[57] DB Chaffin. Human digital modelling for vehicle and workplace design. *Warrendale, PA: Society of Automotive Engineers*, 2001.

[58] Don B Chaffin. Improving digital human modelling for proactive ergonomics in design. *Ergonomics*, 48(5):478–491, 2005.

[59] Don B Chaffin. Digital human modeling for workspace design. *Reviews of Human Factors and Ergonomics*, 4(1):41–74, 2008.

[60] Don B Chaffin. Some requirements and fundamental issues in digital human modeling. *Handbook of digital human modeling*, pages 2–1, 2009.

[61] Don B Chaffin, Cynthia Nelson, et al. *Digital human modeling for vehicle and workplace design*. Society of Automotive Engineers Warrendale, PA, 2001.

[62] John M Charles. *Contemporary kinesiology*. Stipes Publishing, 2002.

[63] Qiliang Chen, Babak Heydari, and Mohsen Moghaddam. Levering task modularity in reinforcement learning for adaptable industry 4.0 automation. *Journal of Mechanical Design*, pages 1–35, 2021.

[64] Jason Tak-Man Cheung and Ming Zhang. Parametric design of pressure-relieving foot orthosis using statistics-based finite element method. *Medical engineering & physics*, 30(3):269–277, 2008.

[65] Hyung Yun CHOI. Potential use of digital human models in sports science and technology. *Journal of the Society of Mechanical Engineers*, 113(1095):96–99, 2010.

[66] Edward James Christie, Daniel D Jensen, Richard T Buckley, Devin A Menefee, Kyle Kenneth Ziegler, Kristin L Wood, and Richard H Crawford. Prototyping strategies: literature review and identification of critical variables. In *American Society for Engineering Education Conference*, 2012.

[67] Daniel Cohen, Nick Sevdalis, Vishal Patel, Michael Taylor, Henry Lee, Mick Vokes, Mick Heys, David Taylor, Nicola Batrick, and Ara Darzi. Tactical and

operational response to major incidents: feasibility and reliability of skills assessment using novel virtual environments. *Resuscitation*, 84(7):992–998, 2013.

[68] Giorgio Colombo and Umberto Cugini. Virtual humans and prototypes to evaluate ergonomics and safety. *Journal of Engineering Design*, 16(2):195–203, 2005.

[69] Giorgio Colombo, De Giorgio Ponti, and Caterina Rizzi. Digital human modeling for ergonomic analysis of refrigerated cabinets. In *ICORD 09: Proceedings of the 2nd International Conference on Research into Design, Bangalore, India 07.-09.01. 2009*, 2009.

[70] Robert G Cooper. *Product leadership: creating and launching superior new products*. Basic Books, 1999.

[71] Euan Ross Coutts, Andrew Wodehouse, and Jason Robertson. A comparison of contemporary prototyping methods. In *Proceedings of the Design Society: International Conference on Engineering Design*, volume 1, pages 1313–1322. Cambridge University Press, 2019.

[72] Umberto Cugini, Monica Bordegoni, and Rossella Mana. The role of virtual prototyping and simulation in the fashion sector. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 2(1):33–38, 2008.

[73] Lucas Santos Dalenogare, Guilherme Brittes Benitez, Néstor Fabián Ayala, and Alejandro Germán Frank. The expected contribution of industry 4.0 technologies for industrial performance. *International Journal of Production Economics*, 204:383–394, 2018.

[74] Michael Deininger, Shanna R Daly, Kathleen H Sienko, and Jennifer C Lee. Novice designers' use of prototypes in engineering design. *Design studies*, 51:25–65, 2017.

[75] Sidney Dekker and Jim Meyer. Book review: Field guide to human error investigations. *Creative Nursing*, 12(3):15–16, 2006.

[76] Sidney WA Dekker. The re-invention of human error. *Human factors and aerospace safety*, 1(3):247–265, 2001.

[77] H. Onan Demirel. *Sensory feedback mechanism for virtual build methodology.* PhD thesis, Purdue University, 2009.

[78] H. Onan Demirel. Digital human-in-the-loop framework. In *Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Posture, Motion and Health*, pages 18–32. Springer, 2020.

[79] H. Onan Demirel and Vincent G Duffy. Applications of digital human modeling in industry. In *International Conference on Digital Human Modeling*, pages 824–832. Springer, 2007.

[80] H. Onan Demirel and Vincent G Duffy. A sustainable human centered design framework based on human factors. In *International Conference on Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management*, pages 307–315. Springer, 2013.

[81] H. Onan Demirel and Vincent G Duffy. Incorporating tactile cues into human-centered virtual product design. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 27(1):5–16, 2017.

[82] Hasan Onan Demirel. *Modular human-in-the-loop design framework based on human factors.* PhD thesis, Purdue University, 2015.

[83] Steven Dow, Julie Fortuna, Dan Schwartz, Beth Altringer, Daniel Schwartz, and Scott Klemmer. Prototyping dynamics: sharing multiple designs improves exploration, group rapport, and results. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2807–2816. Acm, 2011.

[84] Steven P Dow, Alana Glassco, Jonathan Kass, Melissa Schwarz, Daniel L Schwartz, and Scott R Klemmer. Parallel prototyping leads to better design results, more divergence, and increased self-efficacy. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 17(4):18, 2010.

[85] Steven P Dow, Kate Heddleston, and Scott R Klemmer. The efficacy of prototyping under time constraints. In *Proceedings of the seventh ACM conference on Creativity and cognition*, pages 165–174. ACM, 2009.

[86] Jeffrey A Drezner and Meilinda Huang. On prototyping. 2009.

[87] H Dubberly, U Haque, and P Pangaro. What is interaction? are there different types?(2009), 2012.

[88] Vincent G Duffy. Modified virtual build methodology for computer-aided ergonomics and safety. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 17(5):413–422, 2007.

[89] Vincent G Duffy. *Handbook of digital human modeling: research for applied ergonomics and human factors engineering*. CRC press, 2016.

[90] Jan Dul, Ralph Bruder, Peter Buckle, Pascale Carayon, Pierre Falzon, William S Marras, John R Wilson, and Bas van der Doelen. A strategy for human factors/ergonomics: developing the discipline and profession. *Ergonomics*, 55(4):377–395, 2012.

[91] Jan Dul and W Patrick Neumann. Ergonomics contributions to company strategies. *Applied ergonomics*, 40(4):745–752, 2009.

[92] Catherine Elsen, Anders Häggman, Honda Tomonori, and Maria C Yang. Representation in early stage design: An analysis of the influence of sketching and prototyping in design projects. In *Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, page 11. ASME, 2012.

[93] Christer W Elverum and Torgeir Welo. The role of early prototypes in concept development: insights from the automotive industry. *Procedia CIRP*, 21:491–496, 2014.

[94] Ann-Christine Falck and Mikael Rosenqvist. What are the obstacles and needs of proactive ergonomics measures at early product development stages?–an interview study in five swedish companies. *International Journal of Industrial Ergonomics*, 42(5):406–415, 2012.

[95] Francesco Ferrise, Monica Bordegoni, and Umberto Cugini. Interactive virtual prototypes for testing the interaction with new products. *Computer-Aided Design and Applications*, 10(3):515–525, 2013.

[96] R Feyen, Y Liu, D Chaffin, G Jimmerson, and B Joseph. Computer-aided ergonomics: A case study of incorporating ergonomics analyses into workplace design. *Appl Ergon*, 31(3):291—-300, 2000.

[97] Alan J Flisher, Janet Evans, Martie Muller, and Carl Lombard. Brief report: Test–retest reliability of self-reported adolescent risk behaviour. *Journal of Adolescence*, 27(2):207–212, 2004.

[98] Jeffrey M Franc-Law, Michael Bullard, and F Della Corte. Simulation of a hospital disaster plan: a virtual, live exercise. *Prehospital and disaster medicine*, 23(4):346–353, 2008.

[99] Jeffrey Michael Franc-Law, Pier Luigi Ingrassia, Luca Ragazzoni, and Francesco Della Corte. The effectiveness of training with an emergency department simulator on medical student performance in a simulated disaster. *Canadian journal of emergency medicine*, 12(1):27–32, 2010.

[100] Alejandro Germán Frank, Lucas Santos Dalenogare, and Néstor Fabián Ayala. Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, 210:15–26, 2019.

[101] L Frey Law, T Xia, and A Laake. Modeling human physical capability: joint strength and range of motion. *Handbook of Digital Human Modeling, CRC Press, Boca Raton*, 2009.

[102] Clarisse Gaudez and François Cail. Effects of mouse slant and desktop position on muscular and postural stresses, subject preference and performance in women aged 18–40 years. *Ergonomics*, 59(11):1473–1486, 2016.

[103] Valerie J Gawron, Colin G Drury, Rollin J Fairbanks, and Roseanne C Berger. Medical error and human factors engineering: where are we now? *American Journal of Medical Quality*, 21(1):57–67, 2006.

[104] Elizabeth Gerber and Maureen Carroll. The psychological experience of prototyping. *Design studies*, 33(1):64–84, 2012.

[105] RHM Goossens, CJ Snijders, and T Fransen. Biomechanical analysis of the dimensions of pilot seats in civil aircraft. *Applied ergonomics*, 31(1):9–14, 2000.

[106] Dirk Gorissen, Ivo Couckuyt, Piet Demeester, Tom Dhaene, and Karel Crombecq. A surrogate modeling and adaptive sampling toolbox for computer based design. *Journal of Machine Learning Research*, 11(Jul):2051–2055, 2010.

[107] Rush Frederick Green, Thomas J. Hagale, Tamasi George, Glenn A. Hancock, and Steve M. Rice. Digital human modeling in aerospace. In Sofia Scataglini and Gunther Paul, editors, *DHM and Posturography*, pages 549–558. Elsevier, 2019.

[108] Esther Semsei Greenhouse. Human-centered design. *Retrieved from Livable New York: http://www. aging. ny. gov/LivableNY/ResourceManual/DemographicAndSoci alTrends I*, 9, 2012.

[109] Sen Gu, Sheng Su, Cheng Huang, Zhiqiang Song, and Shasha Yuan. A jack-based ergonomic analysis and design of the cockpit of agricultural material handling vehicle. In *International Conference on Applied Human Factors and Ergonomics*, pages 538–550. Springer, 2019.

[110] Roger R Hall. Prototyping for usability of new technology. *International Journal of Human-Computer Studies*, 55(4):485–501, 2001.

[111] Christopher L Hamon, Matthew G Green, Brock Dunlap, Bradley A Camburn, Richard H Crawford, and Daniel D Jensen. Virtual or physical prototypes development and testing of a prototyping planning tool. Technical report, United States Air Force Academy Air Force Academy United States, 2014.

[112] Camilla Arndt Hansen and Ali Gürcan Özkil. From idea to production: A retrospective and longitudinal case study of prototypes and prototyping strategies. *Journal of Mechanical Design*, 142(3), 2020.

[113] Don Harris, Neville A Stanton, Andrew Marshall, Mark S Young, Jason Demagalski, and Paul Salmon. Using sherpa to predict design-induced error on the flight deck. *Aerospace science and technology*, 9(6):525–532, 2005.

[114] Sandra G Hart and Lowell E Staveland. Development of nasa-tlx (task load index): Results of empirical and theoretical research. In *Advances in psychology*, volume 52, pages 139–183. Elsevier, 1988.

[115] John R Hauser, Don Clausing, et al. The house of quality. 1988.

[116] Robert L Helmreich. On error management: lessons from aviation. *Bmj*, 320(7237):781–785, 2000.

[117] Robert L Helmreich and Ashleigh C Merritt. Culture at work in aviation and medicine. *National, organizational and professional influences. Hampshire, UK: Ashgate*, 1998.

[118] Hal W Hendrick. Applying ergonomics to systems: some documented "lessons learned". *Applied ergonomics*, 39(4):418–426, 2008.

[119] Tim Hess and Joshua David Summers. Case study: evidence of prototyping roles in conceptual design. In *DS 75-1: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 1: Design Processes, Seoul, Korea, 19-22.08. 2013*, 2013.

[120] Dan Högberg, Erik Brolin, and Lars Hanson. Concept of formalized test procedure for proactive assessment of ergonomic value by digital human modelling tools in lean product development. In *International Conference on Applied Human Factors and Ergonomics*, pages 425–436. Springer, 2017.

[121] Lars Högberg. Root causes and impacts of severe accidents at large nuclear power plants. *Ambio*, 42(3):267–284, 2013.

[122] Peter Hoonakker, Pascale Carayon, Ayse P Gurses, Roger Brown, Adjhaporn Khunlertkit, Kerry McGuire, and James M Walker. Measuring workload of icu nurses with a questionnaire survey: the nasa task load index (tlx). *IIE transactions on healthcare systems engineering*, 1(2):131–143, 2011.

[123] Imre Horváth and Els Du Bois. Using modular abstract prototypes as evolving research means in design inclusive research. In *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 475–486. American Society of Mechanical Engineers, 2012.

[124] JR Hotchkiss, JD Paladino, CW Brackney, AM Kaynar, and PS Crooke. The language of caring: digital human modeling, practice patterns, and performance assessment. *Procedia Manufacturing*, 3:3788–3795, 2015.

[125] Zhangjun Huang, Chengen Wang, Jian Chen, and Hong Tian. Optimal design of aeroengine turbine disc based on kriging surrogate models. *Computers & structures*, 89(1-2):27–37, 2011.

[126] JD Ianni. Human model evaluations of air force system designs. *Digital human modeling for vehicle and workplace design*, pages 37–55, 2001.

[127] Pier Luigi Ingrassia, Luca Ragazzoni, Luca Carenzo, Davide Colombo, Alba Ripoll Gallardo, and Francesco Della Corte. Virtual reality and live simulation: a comparison between two simulation tools for assessing mass casualty triage skills. *European Journal of Emergency Medicine*, 22(2):121–127, 2015.

[128] K Iwaki. Control room design and automation in the advanced bwr. In *Proc./Ann. Int. Symp. Balancing Automation Human Action in Nuclear Power Plants*, pages 399–412, 1990.

[129] James. James dyson on his vacuum failure and success. `http://nymag.com/vindicated/2016/11/james-dyson-on-5-126-vacuums-that-didnt-work-and-1-that-did.html`. (Accessed on 12/16/2019).

[130] Jooyoung Jang and Christian D Schunn. Physical design tools support and hinder innovative engineering design. *Journal of Mechanical Design*, 134(4):041001, 2012.

[131] Mollie W Jenckes, Christina L Catlett, Edbert B Hsu, Karen Kohri, Gary B Green, Karen A Robinson, Eric B Bass, and Sara E Cosgrove. Development of evaluation modules for use in hospital disaster drills. *American journal of disaster medicine*, 2(2):87–95, 2007.

[132] Johan Jenvald and Magnus Morin. Simulation-supported live training for emergency response in hazardous environments. *Simulation & Gaming*, 35(3):363–377, 2004.

[133] Anders Jönsson. *Lean Prototyping of Multi-body and Mechatronic Systems*. PhD thesis, Blekinge Institute of Technology, 2004.

[134] Barry H Kantowitz and Robert D Sorkin. *Human factors: Understanding people-system relationships*. John Wiley & Sons Inc, 1983.

[135] Gitahi Kariuki and Katharina Löwe. Incorporation of human factors in the design process. *Institute for Plant and Process Technology, Process Safety and Plant Technology, TU, Berlin*, 2012.

[136] Sougata Karmakar, J Sanjog, and Thaneswer Patel. Digital human modeling and simulation in product and workplace design: Indian scenario. *International Journal of Engineering Research and Applications (IJERA) ISSN*, pages 2248–9622, 2014.

[137] Waldemar Karwowski. The discipline of ergonomics and human factors. *Handbook of human factors and ergonomics*, 3:3–31, 2006.

[138] SM Khayer, T Patel, and KN Dewangan. Ergonomic design improvement of pedal thresher: an approach combining digital human modelling and response surface analysis. *J. Ergon. S*, 6(2), 2017.

[139] Sunwook Kim, Hyang Seol, Laura H Ikuma, and Maury A Nussbaum. Knowledge and opinions of designers of industrialized wall panels regarding incorporating ergonomics in design. *International Journal of Industrial Ergonomics*, 38(2):150–157, 2008.

[140] Nelson King and Ann Majchrzak. Concurrent engineering tools: Are the human issues being ignored? *IEEE Transactions on engineering management*, 43(2):189–201, 1996.

[141] Barry Kirwan and Les K Ainsworth. *A guide to task analysis: the task analysis working group*. CRC press, 1992.

[142] Kari Kuutti, Katja Battarbee, Simo Sade, T Mattelmaki, Turkka Keinonen, Topias Teirikko, and A-M Tornberg. Virtual prototypes in usability testing. In *Proceedings of the 34th Annual Hawaii International Conference on System Sciences*, pages 7–pp. IEEE, 2001.

[143] Dan Lämkull, Lars Hanson, and Roland Örtengren. A comparative study of digital human modelling simulation results and their outcomes in reality: A case study within manual assembly of automobiles. *International Journal of Industrial Ergonomics*, 39(2):428–441, 2009.

[144] Carlye Lauff, Jessica Menold, and Kristin L Wood. Prototyping canvas: Design tool for planning purposeful prototypes. In *Proceedings of the Design Society: International Conference on Engineering Design*, volume 1, pages 1563–1572. Cambridge University Press, 2019.

[145] Carlye A Lauff, Daria Kotys-Schwartz, and Mark E Rentschler. What is a prototype? what are the roles of prototypes in companies? *Journal of Mechanical Design*, 140(6):061102, 2018.

[146] K Ronald Laughery. Micro saint—a tool for modeling human performance in systems. In *Applications of human performance models to system design*, pages 219–230. Springer, 1989.

[147] Glyn Lawson, Paul Herriotts, Louise Malcolm, Katharina Gabrecht, and Setia Hermawati. The use of virtual reality and physical tools in the development and validation of ease of entry and exit in passenger vehicles. *Applied ergonomics*, 48:240–251, 2015.

[148] Jay Lee, Behrad Bagheri, and Hung-An Kao. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing letters*, 3:18–23, 2015.

[149] Yong-Gu Lee, Hyungjun Park, Woontaek Woo, Jeha Ryu, Hong Kook Kim, Sung Wook Baik, Kwang Hee Ko, Han Kyun Choi, Sun-Uk Hwang, Duck Bong Kim, et al. Immersive modeling system (imms) for personal electronic products using a multi-modal interface. *Computer-Aided Design*, 42(5):387–401, 2010.

[150] Guohua Li, Susan P Baker, Jurek G Grabowski, and George W Rebok. Factors associated with pilot error in aviation crashes. *Aviation, space, and environmental medicine*, 72(1):52–58, 2001.

[151] Peng Li, Jeremy Carson, Joseph Parham, and Steven Paquette. Digital human modeling pipeline with a 3d anthropometry database. In *Advances in Applied Digital Human Modeling and Simulation*, pages 257–266. Springer, 2017.

[152] Youn-Kyung Lim, Erik Stolterman, and Josh Tenenberg. The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 15(2):7, 2008.

[153] SW Lin, S Mellor, B Miller, J Durand, M Crawford, and R Lembree. Industrial internet reference architecture, version 1.7. *Industrial Internet Consortium. https://www. iiconsortium. org/IIRA-1-7-ajs. pdf. Zugegriffen am*, 3:2020, 2015.

[154] Y-C Liu, A Chakrabarti, and T Bligh. Towards an 'ideal'approach for concept generation. *Design studies*, 24(4):341–355, 2003.

[155] Søren N Lophaven, Hans Bruun Nielsen, Jacob Sondergaard, and A Dace. A matlab kriging toolbox. *Technical University of Denmark, Kongens Lyngby, Technical Report No. IMM-TR-2002-12*, 2002.

[156] Søren Nymand Lophaven, Hans Bruun Nielsen, and Jacob Søndergaard. Dace-a matlab kriging toolbox, version 2.0. 2002.

[157] Yang Lu. Industry 4.0: A survey on technologies, applications and open research issues. *Journal of industrial information integration*, 6:1–10, 2017.

[158] Martin A Makary and Michael Daniel. Medical error—the third leading cause of death in the us. *Bmj*, 353:i2139, 2016.

[159] Russell Marshall, Keith Case, Mark Porter, Steve Summerskill, Diane Gyi, Pete Davis, and Ruth Sims. Hadrian: a virtual approach to design for all. *Journal of Engineering Design*, 21(2-3):253–273, 2010.

[160] Caroline Massolino, Salvador Ávila Filho, Ivone Cerqueira, Renê Pimentel, Napoleão Neto, and Cristiane Fragoso. Ergonomic study to compare digital human modeling simulation versus real life and momentum. In *International Conference on Applied Human Factors and Ergonomics*, pages 503–513. Springer, 2017.

[161] Marco Mazzola, Leonardo Forzoni, Sara D'Onofrio, and Giuseppe Andreoni. Use of digital human model for ultrasound system design: a case study to minimize the risks of musculoskeletal disorders. *International Journal of Industrial Ergonomics*, 60:35–46, 2017.

[162] William C McGaghie, S Barry Issenberg, Emil R Petrusa, and Ross J Scalese. A critical review of simulation-based medical education research: 2003–2009. *Medical education*, 44(1):50–63, 2010.

[163] Michael D McKay, Richard J Beckman, and William J Conover. Comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*, 21(2):239–245, 1979.

[164] Michael D McKay, Richard J Beckman, and William J Conover. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*, 42(1):55–61, 2000.

[165] David Meister. Systems design, development and testing. *Handbook of human factors*, pages 17–42, 1987.

[166] Jessica Menold, Kathryn Jablokow, and Timothy Simpson. Prototype for x (pfx): A holistic framework for structuring prototyping methods to support engineering design. *Design Studies*, 50:70–112, 2017.

[167] RE Moe, Daniel D Jensen, and Kristin L Wood. Prototype partitioning based on requirement flexibility. In *ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 65–77. American Society of Mechanical Engineers, 2004.

[168] Giorgio Musso, Roberta Capra, Raffaella Ricci, and Adriana Salatino. Human factors engineering activities for past, present and future manned space habitats. In Neville Stanton, editor, *Advances in Intelligent Systems and Computing: Advances in Human Aspects of Transportation*, pages 173–182. Springer International Publishing, Cham, 2019.

[169] Arthur GO Mutambara and HE Durrant-Whyte. Estimation and control for a modular wheeled mobile robot. *IEEE Transactions on Control Systems Technology*, 8(1):35–46, 2000.

[170] Anja Naumann and Matthias Rötting. Digital human modeling for design and evaluation of human-machine systems. *MMI-Interaktiv*, 12:27–35, 2007.

[171] D Navinchandra. *Exploration and innovation in design: towards a computational model*. Springer Science & Business Media, 2012.

[172] W Lawrence Neeley, Kirsten Lim, April Zhu, and Maria C Yang. Building fast to think faster: exploiting rapid prototyping to accelerate ideation during early stage design. In *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages V005T06A022–V005T06A022. American Society of Mechanical Engineers, 2013.

[173] Sriya Ngo, Carolyn M Sommerich, and Anthony F Luscher. Digital human modeling of obese & aging workers in automotive manufacturing. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 60, pages 1041–1045. SAGE Publications Sage CA: Los Angeles, CA, 2016.

[174] Diederick C Niehorster, Li Li, and Markus Lappe. The accuracy and precision of position and orientation tracking in the htc vive virtual reality system for scientific research. *i-Perception*, 8(3):2041669517708205, 2017.

[175] Susanna Nilsson and Björn Johansson. A cognitive systems engineering perspective on the design of mixed reality systems. In *Proceedings of the 13th*

Eurpoean conference on Cognitive ergonomics: trust and control in complex socio-technical systems, pages 154–161. ACM, 2006.

[176] Don Norman. *The design of everyday things: Revised and expanded edition.* Constellation, 2013.

[177] Kevin N Otto et al. *Product design: techniques in reverse engineering and new product development.* Tsinghua University Press Co., Ltd, 2003.

[178] G Pahl, W Beitz, J Feldhusen, and K Grote. Engineering design: A systematic approach third edition. *Berlin, Springer Science+ Business Media Deutschland GmbH, 2007. 632*, 2007.

[179] Gerhard Pahl and Wolfgang Beitz. *Engineering design: a systematic approach.* Springer Science & Business Media, 2013.

[180] Jinkyun Park, Wondea Jung, Jaewhan Kim, Jaejoo Ha, and Yunghwa Shin. The step complexity measure for emergency operating procedures—comparing with simulation data. *Reliability Engineering & System Safety*, 74(1):63–74, 2001.

[181] Konstantinos Petrakis, Abigail Hird, and Andrew Wodehouse. The concept of purposeful prototyping: Towards a new kind of taxonomic classification. In *Proceedings of the Design Society: International Conference on Engineering Design*, volume 1, pages 1643–1652. Cambridge University Press, 2019.

[182] Duc Truong Pham and Rosemary S Gault. A comparison of rapid prototyping technologies. *International Journal of machine tools and manufacture*, 38(10-11):1257–1287, 1998.

[183] Patrik Polášek, Marek Bureš, and Michal Šimon. Comparison of digital tools for ergonomics in practice. *Procedia Engineering*, 100:1277–1285, 2015.

[184] Charles Pontonnier, Georges Dumont, Asfhin Samani, Pascal Madeleine, and Marwan Badawi. Designing and evaluating a workstation in real and virtual environment: toward virtual reality based ergonomic design sessions. *Journal on Multimodal User Interfaces*, 8(2):199–208, 2014.

[185] Jorge Posada, Carlos Toro, Iñigo Barandiaran, David Oyarzun, Didier Stricker, Raffaele De Amicis, Eduardo B Pinto, Peter Eisert, Jürgen Döllner,

and Ivan Vallarino. Visual computing as a key enabling technology for industrie 4.0 and industrial internet. *IEEE computer graphics and applications*, 35(2):26–40, 2015.

[186] R Rajesh and R Srinath. Review of recent developments in ergonomic design and digital human models. *Ind Eng Manage*, 5(186):2169–0316, 2016.

[187] Harro Ranter. Asn aircraft accident de havilland canada dhc-8-402q dash 8 s2-agu kathmandu-tribhuvan airport (ktm), Mar 2018.

[188] Ulrich Raschke and Christina Cort. Siemens jack. In Sofia Scataglini and Gunther Paul, editors, *DHM and Posturography*, pages 35–48. Elsevier, 2019.

[189] J Reason. The contribution of latent human failures to the breakdown of complex systems. In *Human Error in Aviation*, pages 5–14. Routledge, 2017.

[190] James Reason. The contribution of latent human failures to the breakdown of complex systems. *Phil. Trans. R. Soc. Lond. B*, 327(1241):475–484, 1990.

[191] James Reason. *Human error*. Cambridge university press, 1990.

[192] James Reason. Human error: models and management. *Bmj*, 320(7237):768–770, 2000.

[193] Matthew P Reed, Sheila M Ebert, Monica LH Jones, and Jason J Hallman. Prevalence of non-nominal seat positions and postures among front-seat passengers. *Traffic injury prevention*, pages 1–6, 2020.

[194] Vasja Roblek, Maja Meško, and Alojz Krapež. A complex view of industry 4.0. *Sage Open*, 6(2):2158244016653987, 2016.

[195] Andreja Rojko. Industry 4.0 concept: background and overview. *International Journal of Interactive Mobile Technologies (iJIM)*, 11(5):77–90, 2017.

[196] Maximiliano Romero, Fiammetta Costa, Giuseppe Andreoni, Marco Mazzola, Juan Vargas, and Luigi Conenna. Proactive ergonomics in refrigerator concept development. In *International Conference on Human Centered Design*, pages 627–634. Springer, 2009.

[197] William J Rothwell, Carolyn K Hohne, and Stephen B King. *Human performance improvement: Building practitioner performance*. Routledge, 2018.

[198] Paul M Salmon, Michael G Lenné, Neville A Stanton, Daniel P Jenkins, and Guy H Walker. Managing error on the open road: The contribution of human error models and methods. *Safety science*, 48(10):1225–1235, 2010.

[199] Gavriel Salvendy. *Handbook of human factors and ergonomics*. John Wiley & Sons, 2012.

[200] Javier Santos, Jose M Sarriegi, Nicolás Serrano, and Jose M Torres. Using ergonomic software in non-repetitive manufacturing processes: A case study. *International Journal of Industrial Ergonomics*, 37(3):267–275, 2007.

[201] Matthew N Saunders, Carolyn C Seepersad, and Katja Hölttä-Otto. The Characteristics of Innovative, Mechanical Products. *Journal of Mechanical Design*, 133(2):021009, 2011.

[202] Mark C Schall Jr, Nathan B Fethke, and Victoria Roemig. Digital human modeling in the occupational safety and health process: An application in manufacturing. *IISE transactions on occupational ergonomics and human factors*, 6(2):64–75, 2018.

[203] RC Schlaepfer, M Koch, and P Merkofer. Challenges and solutions for the digital transformation and use of exponential technologies. *Deloitte. URL: http://deloitte.com/content/dam/Deloitte/ch/Documents/manufacturing/ch-en/manufacturing-industry-4-0-24102014. pdf*, 2015.

[204] Jan Schlechtendahl, Matthias Keinert, Felix Kretschmer, Armin Lechler, and Alexander Verl. Making existing production systems industry 4.0-ready. *Production Engineering*, 9(1):143–148, 2015.

[205] Michael Schrage. *Serious play: How the world's best companies simulate to innovate*. Harvard Business Press, 1999.

[206] SS Shaphiro and MB Wilk. An analysis of variance test for normality. *Biometrika*, 52(3):591–611, 1965.

[207] Scott A Shappell and Douglas A Wiegmann. Us naval aviation mishaps, 1977-92: differences between single-and dual-piloted aircraft. *Aviation, Space, and Environmental Medicine*, 67(1):65–69, 1996.

[208] Alessio Silvetti, Elio Munafò, Alberto Ranavolo, Antonella Tatarelli, Lorenzo Fiori, Sergio Iavicoli, Pasquale Di Palma, and Francesco Draicchio. Ergonomic risk assessment of sea fisherman part iii: Manual handling and static posture. In *International Conference on Applied Human Factors and Ergonomics*, pages 379–392. Springer, 2019.

[209] Carlo Emilio Standoli, Stefano Elio Lenzi, Nicola Francesco Lopomo, Paolo Perego, and Giuseppe Andreoni. Using digital human modeling to evaluate large scale retailers' furniture: Two case studies. In *International Conference on Applied Human Factors and Ergonomics*, pages 512–521. Springer, 2018.

[210] Neville A Stanton and Mark S Young. Giving ergonomics away? the application of ergonomics methods by novices. *Applied Ergonomics*, 34(5):479–490, 2003.

[211] Allison Stephens and Christina Godin. The truck that jack built: Digital human models and their role in the design of work cells and product design. Technical report, SAE Technical Paper, 2006.

[212] David Stowe. Investigating the role of prototyping in mechanical design using case study validation. 2008.

[213] Sultan Sultan, Karim Abdel-Malek, Jasbir Arora, and Rajan Bhatt. Human simulation system for injury assessment due to repetitive loading. In *International Conference on Applied Human Factors and Ergonomics*, pages 131–140. Springer, 2017.

[214] Anders Sundin and Roland Örtengren. Digital human modeling for cae applications. *Handbook of human factors and ergonomics*, pages 1053–1078, 2006.

[215] Stefan Thomke and David E Bell. Sequential testing in product development. *Management Science*, 47(2):308–323, 2001.

[216] Stefan H Thomke. Managing experimentation in the design of new products. *Management Science*, 44(6):743–762, 1998.

[217] Stefan H Thomke. *Experimentation matters: unlocking the potential of new technologies for innovation.* Harvard Business Press, 2003.

[218] Edward Tiong, Olivia Seow, Bradley Camburn, Kenneth Teo, Arlindo Silva, Kristin L Wood, Daniel D Jensen, and Maria C Yang. The economies and dimensionality of design prototyping: Value, time, cost, and fidelity. *Journal of Mechanical Design*, 141(3), 2019.

[219] Mitchell M Tseng, Jianxin Jiao, and Chuan-Jun Su. A framework of virtual design for product customization. In *1997 IEEE 6th International Conference on Emerging Technologies and Factory Automation Proceedings, EFTA'97*, pages 7–14. IEEE, 1997.

[220] Anthony Tzannes, Anastasios Paxinos, Mary Callanan, and George AC Murrell. An assessment of the interexaminer reliability of tests for shoulder instability. *Journal of shoulder and elbow surgery*, 13(1):18–23, 2004.

[221] Karl T Ulrich. *Product design and development*. Tata McGraw-Hill Education, 2003.

[222] Peter van der Meulen and Andreas Seidl. Ramsis–the leading cad tool for ergonomic analysis of vehicles. In *International Conference on Digital Human Modeling*, pages 1008–1017. Springer, 2007.

[223] Trisha Van Zandt and Robert W Proctor. Human factors in simple and complex systems. 2008.

[224] Anneke Vandevelde, Roland Van Dierdonck, Bart Clarysse, et al. The role of physical prototyping in the product development process. *Vlerick Leuven Gent Management School Working Paper Series*, 7, 2002.

[225] Jouke Verlinden and Imre Horváth. Analyzing opportunities for using interactive augmented prototyping in design practice. *AI EDAM*, 23(3):289–303, 2009.

[226] Judy Village, Cory Searcy, Filipo Salustri, and W Patrick Neumann. Design for human factors (dfhf): a grounded theory for integrating human factors into production design processes. *Ergonomics*, 58(9):1529–1546, 2015.

[227] Robert A Virzi, Jeffrey L Sokolov, and Demetrios Karis. Usability problem identification using both low-and high-fidelity prototypes. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 236–243. ACM, 1996.

[228] V Viswanathan and V Kumar. Cognitive effects of physical models in engineering idea generation. *Unpublished PhD dissertation). Texas A&M University, United States of America*, 2012.

[229] Vimal K Viswanathan and Julie S Linsey. Role of sunk cost in engineering idea generation: an experimental investigation. *Journal of Mechanical Design*, 135(12):121002, 2013.

[230] Miriam Walker, Leila Takayama, and James A Landay. High-fidelity or low-fidelity, paper or computer? choosing attributes when testing web prototypes. In *Proceedings of the human factors and ergonomics society annual meeting*, volume 46, pages 661–665. SAGE Publications Sage CA: Los Angeles, CA, 2002.

[231] Matthew B Wall, Karl T Ulrich, and Woodie C Flowers. Evaluating prototyping technologies for product design. *Research in Engineering Design*, 3(3):163–177, 1992.

[232] G Gary Wang. Definition and review of virtual prototyping. *Journal of Computing and Information Science in engineering*, 2(3):232–236, 2002.

[233] Hongtao Wang, Xiaocheng Zhu, and Zhaohui Du. Aerodynamic optimization for low pressure turbine exhaust hood using kriging surrogate model. *International communications in heat and mass transfer*, 37(8):998–1003, 2010.

[234] Juite Wang. Improved engineering design concept selection using fuzzy sets. *International Journal of Computer Integrated Manufacturing*, 15(1):18–27, 2002.

[235] Ru Wang, Jelena Milisavljevic-Syed, Lin Guo, Yu Huang, and Guoxin Wang. Knowledge-based design guidance system for cloud-based decision support in the design of complex engineered systems. *Journal of Mechanical Design*, pages 1–22, 2021.

[236] Wei Wang, You Chao Sun, and FF Kong. Analysis and study of ergonomics on virtual maintenance of civil airplane based on delmia. In *Advanced Materials Research*, volume 44, pages 821–828. Trans Tech Publ, 2008.

[237] S Ward. Getting feedback from users early in the design process: a case study. In *Ergonomics: the Fundamental Design Science, Proceedings of the*

30th Annual Conference of the Ergonomics Society of Australia, pages 22–29. The Ergonomics Society of Australia Canberra, 1994.

[238] CD Wickens, JD Lee, Y Liu, and SEG Becker. Engineering anthropometry and work space design. *An introduction to human factors engineering. 2nd ed. Upper Saddle River, NJ: Pearson Prentice Hall*, pages 243–268, 2004.

[239] Christopher D Wickens, Sallie E Gordon, Yili Liu, et al. An introduction to human factors engineering. 1998.

[240] Hans-Joachim Wirsching. Human solutions RAMSIS. In Sofia Scataglini and Gunther Paul, editors, *DHM and Posturography*, pages 49–55. Elsevier, 2019.

[241] Jeremy M Wolfe, Keith R Kluender, Dennis M Levi, Linda M Bartoshuk, Rachel S Herz, Roberta L Klatzky, Susan J Lederman, and Daniel M Merfeld. *Sensation & perception*. Sinauer Sunderland, MA, 2006.

[242] Carly Wolkiewicz, Katherine Collins, Faisal Aqlan, and Osama T Al Meanazel. Ergonomic assessment of snow shovels using digital human modeling. In *Proceedings of the International Conference on Industrial Engineering and Operations Management*, volume 2018, pages 1146–1153, 2018.

[243] Ingrid Anette Wulff, Bente Rasmussen, and Rolf H Westgaard. Documentation in large-scale engineering design: information processing and defensive mechanisms to generate information overload. *International Journal of Industrial Ergonomics*, 25(3):295–310, 2000.

[244] Song Xu, Fei Song, Zhizhong Li, Qianyi Zhao, Wei Luo, Xuhong He, and Gavriel Salvendy. An ergonomics study of computerized emergency operating procedures: presentation style, task complexity, and training level. *Reliability Engineering & System Safety*, 93(10):1500–1511, 2008.

[245] Zhang Yumei and Wang Wugui. Ergonomics simulation and evaluation application for the wheelhouse on large ships. In *International Conference on Applied Human Factors and Ergonomics*, pages 501–511. Springer, 2018.

[246] Mohsen Zare, Michel Croq, Farhad Hossein-Arabi, Rene Brunet, and Yves Roquelaure. Does ergonomics improve product quality and reduce costs? a review article. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 26(2):205–223, 2016.

[247] Lauren Wood Zaseck, Anne C Bonifas, Carl S Miller, Nichole Ritchie Orton, Matthew P Reed, Constantine K Demetropoulos, Kyle A Ott, Christopher J Dooley, Nathanael P Kuo, Leah M Strohsnitter, et al. Kinematic and biomechanical response of post-mortem human subjects under various pre-impact postures to high-rate vertical loading conditions. Technical report, SAE Technical Paper, 2020.

[248] Gregory F Zehner, Jeffrey A Hudson, and Aernout Oudenhuijzen. Attempting to train a digital human model to reproduce human subject reach capabilities in an ejection seat aircraft. Technical report, SAE Technical Paper, 2006.

[249] SC Zemke. Student learning in multiple prototype cycles. In *ASEE annual Conference and Exposition*, volume 3, 2012.

[250] Xudong Zhang and Don B Chaffin. Digital human modeling for computer-aided ergonomics. *Handbook of Occupational Ergonomics. Taylor & Francis, CRC Press, London, Boca Raton*, pages 1–20, 2005.

[251] Wenmin Zhu, Xiumin Fan, and Yanxin Zhang. Applications and research trends of digital human models in the manufacturing industry. *Virtual Reality & Intelligent Hardware*, 1(6):558–579, 2019.

[252] Farbod Zorriassatine, Catherine Wykes, Robert Parkin, and Nabil Gindy. A survey of virtual prototyping techniques for mechanical product development. *Proceedings of the institution of mechanical engineers, Part B: Journal of engineering manufacture*, 217(4):513–530, 2003.

APPENDICES

Appendix A: Prototyping Findings

Table 2: Step 2: Prototyping Findings

Prototyping Dimensions			Prototyping Findings
1. Type of Prototype	*1.0. Physical*	1.1.1.	Physical prototypes are created for the purpose of exploring design, communicating ideas, support and improvement of creative ideas, learning new information, verifying the design criteria and for integrating and passing specification into later design activities [47, 225, 228]
		1.1.2.	It is an effective way to experience the shape, composition, and functionality. Three-Dimensional physical prototypes instantly help to comprehend all shape relations [47].
		1.1.3.	A physical prototype helps in exploring design space by providing rapid visual and tactile feedback [46].
		1.1.4.	Ergonomic analysis of a product is done by creating a complete physical mock-up, assembly workspace along with the real people in various combination to find optimum ergonomic design [28].
		1.1.5.	Physical prototyping is time-consuming to build, costly, inflexible and prone to error for data collection [40]
		1.1.6.	Each round of design modification requires creating another new physical prototype, thus adding a lot of resources like time and finances to the development program [40]
		1.1.7.	Physical prototyping is difficult or impossible to change or add further modifications once it is made. This inflexibility also poses a problem when new design ideas need to be prototyped after receiving new revisions and feedbacks [252].
		1.1.8.	Physical prototype is preferred to create high fidelity prototypes [93, 221].
		1.1.9.	Physical prototypes are preferred to identify unanticipated phenomenon. [221]
	1.2. Computational	1.2.1.	Computational prototypes used in the conceptual stage can help to reduce the use of physical prototyping, thus reducing time and finances [169]
		1.2.2.	Computational prototypes have better accuracy in terms of size, dimension, shape, geometry etc. [41].
		1.2.3.	It can give a concrete demonstration of the product hence simplifying the communication between stakeholder, designers and decision-makers [51]. It can be used for rapid interantional communication [72]
		1.2.4.	Computational prototypes can render photorealistic images and the file can be transferred in any part of the world thus giving the advantage of global transferability [142]
		1.2.5.	Computational prototype using Digital Human Modeling (DHM) can be used to accomplish proactive ergonomics for human-centered product design [58]
		1.2.6.	DHM can also be used for product design, reduce the need for a physical prototype, crash testing, etc. [45].
		1.2.7.	It can be used to do ergonomic analysis such as spatial accommodation, comfort, and posture prediction, clearance/interference of body segments, biomechanical stress, visibility check, reach and grasp, task evaluation and safety, multi-person interaction etc. [89, 214]
		1.2.8.	One major limitation of DHM is the fidelity or accuracy of predicting what task can people perform safely [60]
		1.2.9.	DHM requires further development for correctly predicting work task's real outcome, i.e. hand access, push pressure and pull forces, leaning and balance behavior, field of vision and high-level series of task [58, 143].
		1.2.10.	The cognitive DHM is not well-developed as the physical DHM [58, 214].
		1.2.11.	The computational prototype has lower validity and reliability than physical prototype [147]
		1.2.12.	In Computational prototyping, there is no real user so the there is a lack of interaction between the evaluator and user and therefore it restricts the amount of feedback information [142]
		1.2.13.	Computation prototype does not provide any haptic feedback, feel of the material, weight, etc. [142, 184]
		1.2.14.	Computational Prototype helps to identify flaws and modify the design early in the design process [51]
		1.2.15.	For relatively simple design problem, unsafe, hazardous, "what-if" scenarios, computational prototypes performs better than physical prototype [61, 111]
	1.3. Mixed	1.3.1.	Mixed Prototyping uses the interactive and immersive technologies that enable human-product interaction which open novel venues to create prototyping strategies to add visual realism, auditory realism, tactile realism, functional realism [44, 175].
		1.3.2.	It is limited for digital applications where design interfaces are based on touch screens. Thus, it would become difficult if not impossible to represent various interfaces with only one physical prototype [36]
		1.3.3.	Mixed prototype based on virtual reality is more suitable to assess reach, visibility and use of tools compare to mixed prototypes based on augmented reality [33]
		1.3.4.	Mixed prototypes can be used for cognitive ergonomic assessment [22, 25]
		1.3.5.	Mixed Prototype is a mix between physical and computational prototype, thus retaining the advantages and disadvantages of each type [36, 44].
		1.3.6.	Mixed prototypes can be used where physical prototyping is infeasible or unsafe and where computational prototyping lacks accuracy [22, 25, 55]
2. Fidelity		2.1.	A high fidelity prototype reveals more usability problems than the original low fidelity prototype. The instant visual feedback and more realistic interaction helped to get more feedback from the user, thus, revealing more problems [110].
		2.2.	High fidelity prototypes require high cost of resources such as time and finances [110].
		2.3.	Potential problems can be identified from low fidelity prototypes which are low cost and time saving to build [110, 237].
		2.4.	Low fidelity prototypes that are rough and quick to make but model the main attributes of design are preferable to time-consuming high fidelity prototypes [46]
		2.5.	It is found that low fidelity prototypes might not evaluate the physical attributes such as tactile, auditory and visual feedback properly [142].
		2.6.	Low fidelity prototypes facilitates multiple quick iterations which gives a sense of progression, reduces design fixation and concept expression [55, 104, 215]
3. Complexity		3.1.	Prototyping only a part of the system can reduce the cost [86]
		3.2.	Prototyping only a subsystem provides the opportunity to create prototypes focused only on the subsystem for in-depth exploration [66, 123]
		3.3.	Hierarchical Task Analysis can be used to determine what part of the system needs to be prototyped. [16]
4. Build Phase		4.1.	It is recommended to use prototyping early in the design stage to identify the human requirements [32, 130]
		4.2.	Creating a prototype early in the design process causes better technical quality [83, 92].
5. Scale		5.1.	A scaled-down prototype can help in creating full-scale infeasible prototype thus reducing the cost of resources [66, 177]
		5.2.	Increased or decreased scale of the prototype can be used for user interface evaluation [66]
6. Number of Iterations		6.1.	Iteration assists refinement, in-depth insights and gradually accomplishing the design goals, thus improving the end product [55, 66, 85, 172, 249].
		6.2.	Multiple iterations can be helpful to expand and/or refine a particular feature set of a prototype [205, 217]
		6.3.	Parallel prototyping causes better design result by creating a variety of design concepts. It also help in design exploration [84, 167]
		6.4.	Faster iterations reduces design fixation [55, 229]
		6.5.	Designers can decide to iterate or not based on the expected outcome and expected cost of each additional iteration [215]

Appendix B: Summary of Prototyping Findings

Prototype Dimensions		Summary of Findings	Prototyping Findings from Table 1
Type of Prototype	*Physical*	Provides exploration, refinement, learning, communication of ideas	1.1.1., 1.1.2.
		Provides ergonomic assessment for multiple complex physical and/or cognitive task and high human-product interaction	1.1.4. 1.1.3.
		Provides tactile feedback	1.1.5., 1.1.6.
		Requires high resources, i.e. cost and time, less flexibility	1.1.7.
	Computational	Facilitates communication and transfer of ideas	1.2.3., 1.2.4.
		Facilitates learning and improvement early in the design process	1.2.14.
		For ergonomic assessment of single or few simple physical task for low human-product interaction, computational is preferable over physical	1.2.9. 1.2.15.
		Provides ergonomics assessment in a shorter time with less cost	1.2.1.
		Provides ergonomic assessment where creating physical prototype is infeasible	1.2.16.
		Multiple task analysis and Cognitive assessment is limited	1.2.8., 1.2.10.
	Mixed	Provides ergonomic assessment for moderate to simple physical and/or cognitive task	1.3.4.
		Limited tactile feedback	1.3.2
		It has some capabilities and limitations of both physical and computational prototype	13.5
		Can be used where physical prototype is infeasible or unsafe and computational prototype lacks fidelity	1.3.6.
Fidelity	*High*	Provides accurate ergonomic assessment	2.1.
		Provides feedback of finer details	2.1.
		Requires more resources, i.e. cost and time	2.2.
	Low	Provides rough ergonomic assessment	2.4., 2.5.
		Provides limited tactile, auditory and visual feedback	2.5.
		Requires less cost and time to build	2.3.
		Useful for creating quick multiple iterations, reducing design fixation and concept expression and exploration	2.6
Complexity	*Sub-System*	Requires less resources	3.1.
		Provides in-depth exploration and focused ergonomic assessment only for a particular sub-system	3.2.
		Requires HTA to decide what sub-system to prototype	3.3.
	Full System	Requires more resources	3.1.
		Provides ergonomic assessment for the full system	3.2.
Build Phase		Create prototypes early	4.1., 4.2.
Scale	*Full Scale*	Create full scale prototypes if the budget allow	5.1
	Altered	Create increased/decreased scale prototype for user evaluation	5.2
Iteration	*Single*	Provides lower number of feedback with less in-depth insight	6.1
		Requires less resources	6.1
	Multiple	Useful for refinement, gradual goal accomplishment, higher quality feedback and improved end product	6.1., 6.2.
		Parallel iteration useful for concept exploration	6.3., 6.4.
		Quick iterations reduces design fixation	6.4.
		Cost of new information vs cost of iteration can guide number of iterations	6.5.

Figure 1: Step 2: Summary of Prototyping Findings

Appendix C: An Example of Physical Toolbox and Standards

	Examples of Physical Prototyping Tool	
High Interaction	Low End Rapid Prototyping Low End 3D Printed Cardboard, Foams, etc.	High End Rapid Prototyping High End 3D Printed Clay, Wood, Metal, etc.
Low Interaction	Using Pencil and Paper -Rough Story Boarding -Rough 3D Sketch -Rough 2D Sketch	Using Pencil and Paper -Detailed Story Boarding -Detailed 3D Sketch -Detailed 2D Sketch
	Low Fidelity	**High Fidelity**

**List of Some Standard tools and Guidelines that might be useful*	
Standards	Occupational Safety and Health Act (OSHA), Federal Aviation Administration (FAA), National Highway Traffic Safety Administration (NHTSA), Society of Automotive Engineers (SAE), etc.
Anthropometry Database	Ansur, Ansur II, Chinese, German, Japanese
Biomechanics Tools	Surface Electromyography (sEMG): For measuring electrical activity of muscles Goniometers: For measuring joint angles
Physical Assessment Tools	Posture Evaluations: Workplace Ergonomic Risk Assessment (WERA), Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA) , NIOSH Lifting Equation Product Evaluation: Ergonomic Seating Evaluation Form, Healthcare Computer Cart Ergonomic Checklist
Cognitive Assessment Tools	Mental Workload Assessment: NASA-TLX, SWAT Task Analysis Techniques: HTA Human Error: SHERPA, HET, TAFEI Performance Time Prediction: The Keystroke Level Model (KLM), Timeline Analysis Situation Awareness Assessment Techniques: SAGAT, SPAM, SART

Figure 2: An Example of Physical Toolbox and Standards

Appendix D: Pre-Prototyping Problem Statements and Solutions

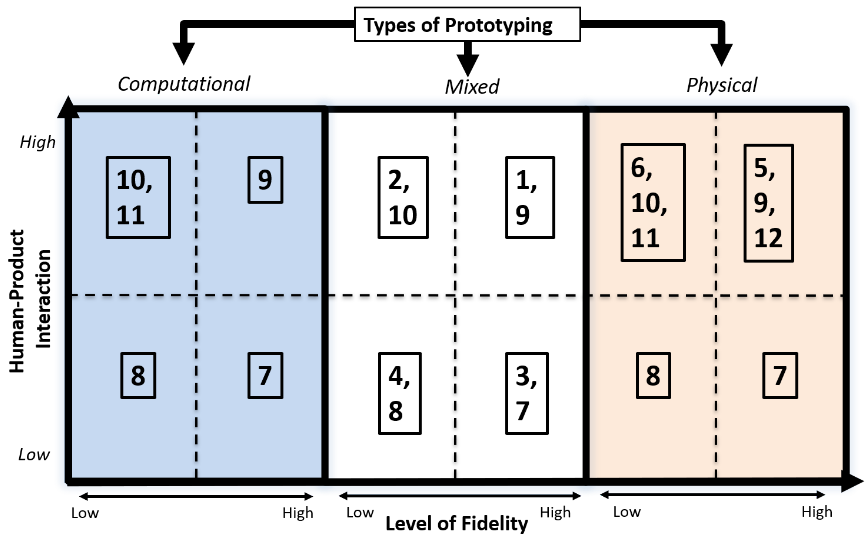


Figure 3: Spread of Prototyping Problem Statements

1. You are to conceptualize a prototyping strategy that can assess a pilot's performance of following the standard protocol during an emergency of fire and smoke in the cockpit. The standard protocol contains a sequence of events such as a pilot is trying to reach an oxygen mask, switch off the power supply, and reach the fire extinguisher. You are to conceptualize prototyping strategies that can evaluate the pilot's performance of vision (field of view), reach posture (joint angles), and mental workload during the emergency event. You are given high resources.

   Solution:

   Prototyping Categories

   Purpose: Learn

Resource: High

Ergonomic Assessment: Physical (Multiple) and Cognitive

Interaction: High

Prototyping Dimensions

Type of Prototype: Mixed Prototype

Fidelity Level: High Fidelity

Complexity: Sub Complexity

Scale: Same

Number of Iterations: Multiple (Sequential)

2. You are to conceptualize a prototyping strategy that can assess a pilot's performance of following the standard protocol during an emergency of fire and smoke in the cockpit. The standard protocol contains a sequence of events such as a pilot is trying to reach an oxygen mask, switch off the power supply, and reach the fire extinguisher. You are to conceptualize prototyping strategies that can evaluate the pilot's performance of vision (field of view), reach posture (joint angles), and mental workload during the emergency event. You are given low resources.

   Solutions:

   Prototyping Categories

   Purpose: Learning

   Resource: High

   Ergonomic Assessment: Physical (Multiple) and Cognitive

Interaction: High

Prototyping Dimensions

Type of Prototype: Mixed Prototype

Fidelity Level: Low Fidelity

Complexity: Sub Complexity

Scale: Same

Number of Iterations: Multiple (Sequential)

3. You are to conceptualize a prototyping strategy that can assess a pilot's performance of following only a section of the standard protocol during an emergency of fire and smoke in the cockpit. This section of the standard protocol contains the pilot trying to reach only the oxygen mask. You are to conceptualize prototyping strategies that can evaluate the pilot's reach posture (joint angles) during the emergency event. You are given high resources.

   Solutions:

   Prototyping Categories

   Purpose: Learning

   Resource: High

   Ergonomic Assessment: Physical (Multiple) and Cognitive

   Interaction: Low

   Prototyping Dimensions

   Type of Prototype: Mixed Prototype

   Fidelity Level: High Fidelity

Complexity: Sub Complexity

Scale: Same

Number of Iterations: Multiple (Sequential)

4. You are to conceptualize a prototyping strategy that can assess a pilot's performance of following only a section of the standard protocol during an emergency of fire and smoke in the cockpit. This section of the standard protocol contains the pilot trying to reach only the oxygen mask. You are to conceptualize prototyping strategies that can evaluate the pilot's reach posture (joint angles) during the emergency event. You are given low resources.

   Solutions:

   Prototyping Categories

   Purpose: Learning

   Resource: Low

   Ergonomic Assessment: Physical (Multiple) and Cognitive

   Interaction: Low

   Prototyping Dimensions

   Type of Prototype: Mixed Prototype

   Fidelity Level: Low Fidelity

   Complexity: Sub Complexity

   Scale: Same

   Number of Iterations: Multiple (Sequential)

Problem 1 to 4 is adapted from the following references [24, 25]

5. You are to conceptualize a prototyping strategy that can be used to design an instrument panel of a submarine. There are multiple switches, buttons, levers, each having its unique shape, size, and tactile feedback. Some of them have limited accessibility due to shield guarding them. There are various performance shaping factors at play such as brightness, climate, auditory, time sensitivity, etc. You are given high resources.

   Solutions:

   Prototyping Categories

   Purpose: Learning

   Resource: High

   Ergonomic Assessment: Physical (Multiple) and Cognitive

   Interaction: High

   Prototyping Dimensions

   Type of Prototype: Physical Prototype

   Fidelity Level: High Fidelity

   Complexity: Sub Complexity

   Scale: Same

   Number of Iterations: Multiple (Sequential)

6. You are to conceptualize a prototyping strategy that can be used to design an instrument panel of a submarine. There are multiple switches, buttons,

levers, each having its unique shape, size, and tactile feedback. Some of them have limited accessibility due to shield guarding them. There are various performance shaping factors at play such as brightness, climate, auditory, time sensitivity, etc. You are given low resources.

Solutions:

Prototyping Categories

Purpose: Learning

Resource: Low

Ergonomic Assessment: Physical (Multiple) and Cognitive

Interaction: High

Prototyping Dimensions

Type of Prototype: Physical/Mixed Prototype

Fidelity Level: Low Fidelity

Complexity: Sub Complexity

Scale: Same

Number of Iterations: Multiple (Sequential)

Problem 5 to 6 adapted from reference [36]

7. You are to create a conceptual prototyping strategy that can be used to design a kitchen sink such that the user can have adequate reaching access/clearance to every four corners of the sink. You are given high resources.

   Solutions:

Prototyping Categories

Purpose: Learning

Resource: High

Ergonomic Assessment: Physical

Interaction: Low

Prototyping Dimensions

Type of Prototype: Physical/Computational/Mixed Prototype

Fidelity Level: High Fidelity

Complexity: Sub Complexity

Scale: Same

Number of Iterations: Multiple (Sequential)

8. You are to conceptualize a prototyping strategy that can be used to design a kitchen sink such that the user can have adequate reaching access to every four corners of the sink. You are given low resources.

   Solutions:

   Prototyping Categories

   Purpose: Learning

   Resource: Low

   Ergonomic Assessment: Physical

   Interaction: Low

   Prototyping Dimensions

   Type of Prototype: Physical/Computational/Mixed Prototype

Fidelity Level: Low Fidelity

Complexity: Sub Complexity

Scale: Same

Number of Iterations: Multiple (Sequential)

Problem 7 to 8 adapted from references [19, 20]

9. You are to conceptualize a prototyping strategy to design a cockpit to improve the pilot's reaching and vision performance during landing an aircraft. During an aircraft landing, the pilot visually confirms the taxiway through the windshield and reaches flap switches and landing gear switches in the instrument panel. You can adjust the orientation of the instrument panel and pilot seat to enhance his/her vision and reach performance. You are given high resources.

   Solutions:

   Prototyping Categories

   Purpose: Learning

   Resource: High

   Ergonomic Assessment: Physical (Multiple)

   Interaction: High

   Prototyping Dimensions

   Type of Prototype: Physical/Computational/Mixed Prototype

   Fidelity Level: High Fidelity

Complexity: Sub Complexity

Scale: Same

Number of Iterations: Multiple (Sequential)

10. You are to conceptualize a prototyping strategy to design a cockpit to improve the pilot's reaching and vision performance during landing an aircraft. During an aircraft landing, the pilot visually confirms the taxiway through the windshield and reaches flap switches and landing gear switches in the instrument panel. You can adjust the orientation of the instrument panel and pilot seat to enhance his/her vision and reach performance. You are given low resources.

    Solutions:

    Prototyping Categories

    Purpose: Learning

    Resource: Low

    Ergonomic Assessment: Physical (Multiple)

    Interaction: High

    Prototyping Dimensions

    Type of Prototype: Physical/Computational/Mixed Prototype

    Fidelity Level: Low Fidelity

    Complexity: Sub Complexity

    Scale: Same

    Number of Iterations: Multiple (Sequential)

Problem 9 and 10 is adapted from the following references [16, 23]

11. You are to conceptualize a prototyping strategy to design a loading cart for a manufacturing plant. You are asked to find out the maximum loading and unloading that an average male worker should perform safely to and from the cart. You are given low resources.

    Solutions:

    Prototyping Categories

    Purpose: Learning

    Resource: Low

    Ergonomic Assessment: Physical

    Interaction: High

    Prototyping Dimensions

    Type of Prototype: Physical/Computational Prototype

    Fidelity Level: Low Fidelity

    Complexity: Sub Complexity

    Scale: Same

    Number of Iterations: Multiple (Sequential)

    Problem 11 adapted from the following reference [202]

12. You are to conceptualize a prototyping strategy that can be used for ergonomic assessment (tactile feedback, comfort) of three different types of the

mouse (regular, slanted, and vertical). You are given high resources.

Solutions:

Prototyping Categories

Purpose: Learning

Resource: High

Ergonomic Assessment: Physical

Interaction: High

Prototyping Dimensions

Type of Prototype: Physical Prototype

Fidelity Level: High Fidelity

Complexity: Sub Complexity

Scale: Same

Number of Iterations: Multiple (Sequential)

Problem 12 adapted from the following reference [102]