A COMMON TAXONOMY FOR MODELING CONSTRUCTION OPERATIONS

Sami K. Al-Masalha

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Environmental Design and Planning

Dr. Ron Wakefield, Chairman

Dr. Yvan Beliveau

Professor Thom Mills

Professor Robert Schubert

Professor Michael O'Brien

August, 2004
Blacksburg, Virginia

Keywords:

Construction simulation, Modeling of Construction Operations, Construction Taxonomy, Virtual Modeling.

A Common Taxonomy for Modeling Construction Operations

By

Sami Al-Masalha

Ron Wakefield, Chairman

Department of Building Construction

Environmental Design and Planning Ph.D. Program

(ABSTRACT)

The construction industry continues to strive for new ways to improve construction operations. This requires better understanding and analysis of these operations, which necessitates a way to systematically capture and analyze the diverse elements involved. The dynamic nature of construction is very difficult to describe using existing computer simulation and modeling systems. What is needed is rather a common construction language and a comprehensive modeling system that can be used to capture and analyze construction operations and potentially lead to improvements.

A new taxonomy and its use for modeling construction operations are developed here. This taxonomy identifies a hierarchical representation of construction projects based on operational considerations. The hierarchy consists of seven levels: product, assemblies and subassemblies, components, operations, processes, physics, and control. The hierarchical levels were established by looking in the ways that construction field operations are being carried out. The new modeling system successfully accounts for the geometric and physical representations of not only the product but also the processes involved in shaping the product. Six major blocks of construction knowledge are described and information about the interaction processes required to model construction operations in a logical way is provided.

An overview of the current state of modeling and simulation techniques that are used to develop and evaluate construction operations is presented. The advantages and limitations of physical-based modeling, 4D-CAD, and virtual modeling techniques as an integral part of the developed taxonomy are identified. The potential uses of robotics and automation opportunities in construction are described. Also, distribution of work between humans and tools and equipment based on their physical and information contributions are reviewed and analyzed. Classifications of construction work at different levels of detail are described to identify which operations can be usefully modeled and the appropriate level of the model.

Two practical case studies are discussed that show the capabilities and potential uses of the developed taxonomy. The first case study describes the modeling process of the fabrication, assembly, and erection of steel structures. The second exploratory case study shows the potential use of the developed modeling in improving the heat recovery system generator's (HRSG) erection process. Also, prototype models and 3D models of the HRSG assemblies are developed. Both case studies validate with great confidence the use of the developed taxonomy as a direct support tool that captures the diverse elements and enhances the modeling and analysis to improve construction operations.

ACKNOWLEDGMENTS

I would like to thank Professor Ron Wakefield for his invaluable guidance and advice throughout my Ph.D. studies. His encouragement, thoughtfulness, and willingness to help are deeply appreciated. His resourcefulness and patience are greatly admired. It has been my pleasure to have him as a friend and a mentor.

I would like also to thank my committee members: Professor Yvan Beliveau for his support, it is an honor to have worked with him and learned from him; Professor Thom Mills for his inspiring ideas and expert advice; Professor Robert Schubert for his advice and encourgment; and Professor Michael O'Brien for his thoughtfulness, invaluable comments, and fresh ideas.

I would like to thank all the people and friends I have met at Black & Veatch. In particular, I would like to thank Mr. Randy Paulson, Mr. Luis Jiminez, Mr. Dan Sullivan, Mr. Jeremy Nichols, Mr. Greg Smith, Mr. Sandy Morman, Mr. Leigh Formanek, and Mr. Stan Shilling, for their friendship and expert advice.

Special acknowledgements are due to the following persons: Dr. Isam Janajreh, Dr. Haider Arafat, Dr. Ziad Masoud, Mr. Samih Zamzam, Dr. Naim Jaber, Dr. Khaled Alhazza, Dr. Ahmed Harb, Dr. Osama Ashour, and Dr. Eihab Abdel-Rahman for their friendship, companionship, hospitality, and kindness.

Most importantly, I would like to thank my family without whose support, I would have never reached this point: my father, Khamis, and my mother, Khadejah, whose accomplishments, boundless eneregy, and words of wisdom are great sources of inspiration to me; my sister, Khawther, and my brothers, Hani and Samer, who throughout the years tolerated their brother, filled his life with fun and happiness, encourged him, and stood by him through thick and thin; my wife, Dana Abdeen, to whom I am forever grateful for the love, kindness, sensibility, and devotion she showed me from day one; and my newborn son, Nizar, whose very presence made me appreciate the little things in life. Finally, thanks goes to All Mighty Allah for giving me the ability, mindset, and perservance to be where I am now.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE: RESEARCH OVERVIEW

1.1 INTRODUCTION

“Building” is a team effort where many entities and activities have to be precisely defined by the architecture, engineering and construction (AEC) team. The main goal of the AEC team is to integrate their efforts to produce an efficient constructed facility. This goal is difficult to achieve because each group is working on the project from a different perspective and in different phases. Furthermore, each group has their own language and tools of representation.

In current practice (see Figure 1.1 and Figure 1.2), designers use paper sketches to present their schematic and preliminary ideas to clients. Then, they often transfer the final drawings to the computer by using a Computer Aided Design (CAD) tool. Engineers use the CAD drawings to design the corresponding mechanical, structural, and HVAC systems. For the engineer, CAD tools are very powerful in managing measurements and exact numbers. Finally, the construction producer or contractor face problems such as visualizing the design, translating the design into a feasible physical reality, designing

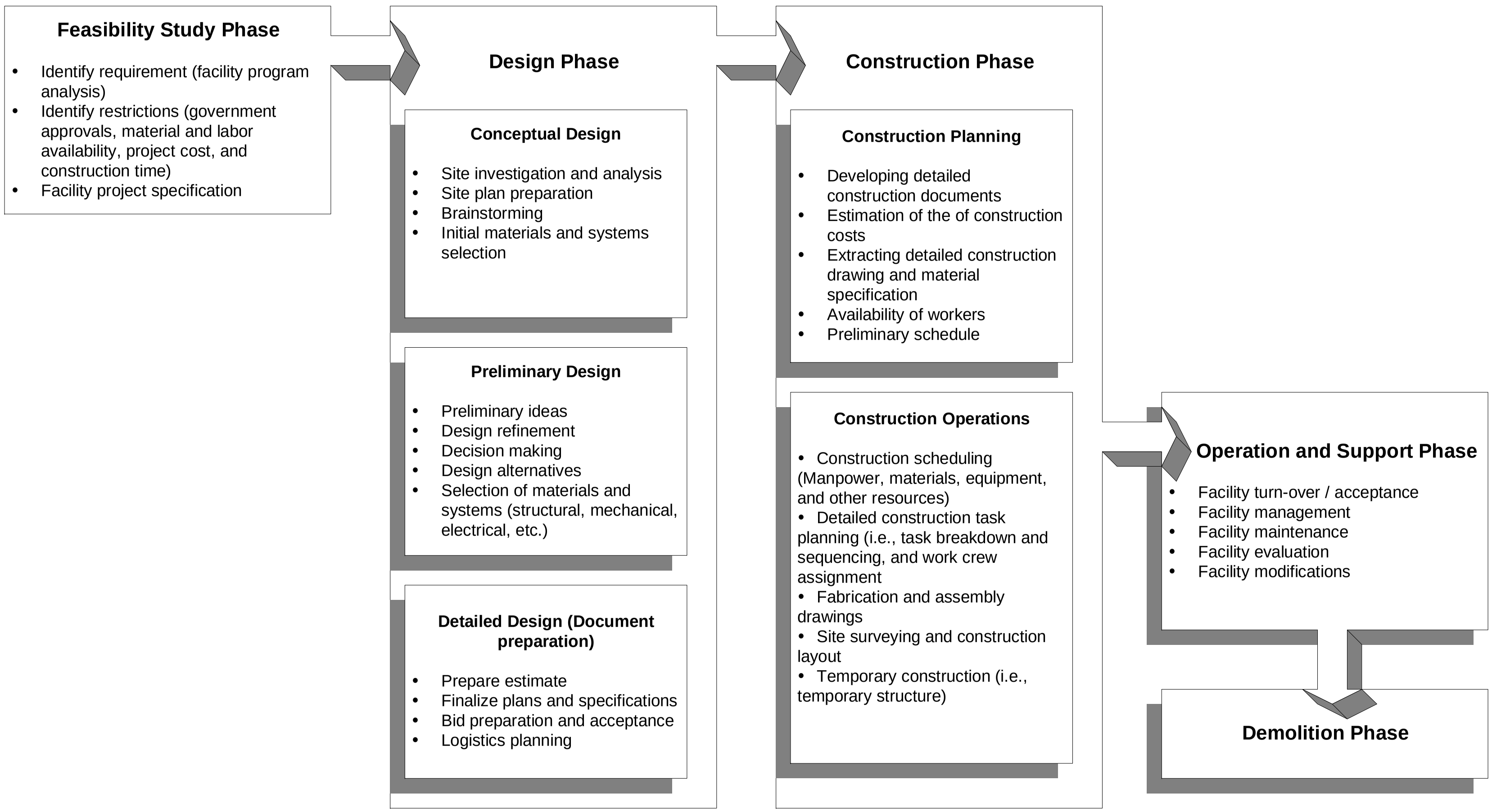


Figure 1.1: The separation between design processes and construction operations (Al-Masalha and Wakefield, 2000).

construction operations and processes and making changes due to unexpected problems that might come about during actual construction.

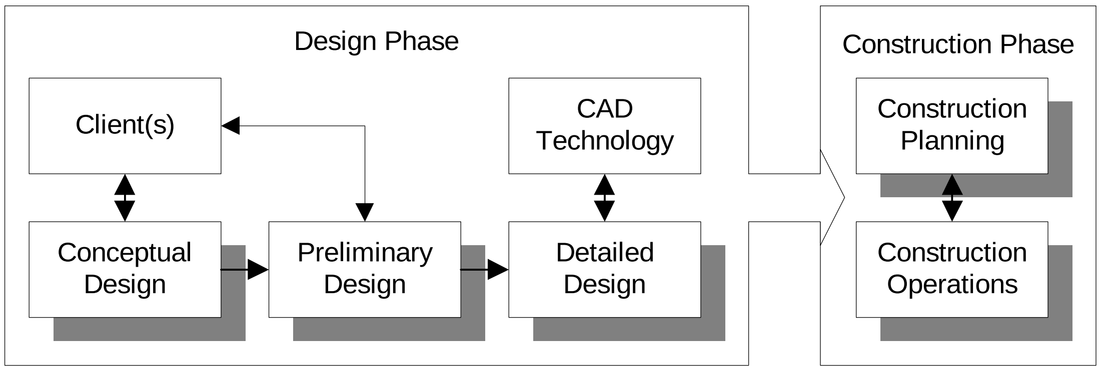


Figure 1.2: The traditional design process.

Current practices have isolated the designers from the production phase of the project. As technology has become more complex, this isolation has created a gap between "how to design a facility" and "how to build a facility". As a result, some designers don't take into consideration how a designed facility is to be constructed. Once the design is completed, the producers or the contractors work on planning and designing the required construction operations to construct the designed facility (Al-Masalha and Wakefield, 2000).

The way we do construction today is a result of prior experiences, mistakes and technical advances. Moreover, design of construction operations is a dynamic process that is becoming more complex. This complexity imposes difficulties specifically on construction planners and designers who are trying to describe and design construction operations, incorporate new technologies, develop new means and methods, and predict problems that might appear during actual construction. In general, construction processes are difficult to describe due to the multiple and complex relationships that exist between the various components of the constructed facility.

To overcome the aforementioned challenges, simulation networks were used to design construction operations and analyze its behavior. However, the dynamic nature of construction is very difficult to describe or model using the existing simulation methods (Opdenbosh, 1994, and Naji 1997). What is needed is rather a common construction language and an effective modeling system that can be used to capture, model, evaluate, and improve construction operations and processes.

To respond to these challenges, this research investigates and develops a new common taxonomy for modeling construction operations. The development of the taxonomy requires applying several types of knowledge from different areas, including construction operations and processes, physically-based modeling, virtual modeling, and construction classifications. Increased understanding of these types of knowledge combined with the common construction taxonomy presents a major opportunity for improving construction operations.

1.2 RESEARCH PROBLEM

In the last three decades, new construction methods have been developed. These methods introduce new products and processes that are changing the way facilities are being constructed. Furthermore, the adaptation of current advanced technologies to the construction domain has enhanced the understanding and improved the design and construction processes (Opdenbosch, 1994; Naji, 1997; Beliveau et al., 1998; and

Wakefield, 1999). Still, the construction industry continues to strive for further improvements. Improvements to construction operations is not something that happens by accident or by good luck; it is achieved through systematic assessment of existing means and methods to support enhancement to construction products and processes. Modeling and simulation techniques are very promising for studying and analyzing construction products and processes.

Existing modeling and simulation techniques, such as Monte Carlo simulation, try to represent and explain construction processes and techniques, but do not consider the geometric components, physical properties, and surrounding environment of the designed facility (Opdenbosch, 1994, and Al-Masalha and Wakefield, 2000). Nonetheless, the geometric representations of the construction elements and their physical behaviors are important factors that influence the modeling of construction operations (Oloufa, 1992, and Al-Masalha and Wakefield, 2000). Other methods attempt to simulate construction operations by relying on geometric objects moving through an abstract space (Hendrickson and Rehak, 1993), but they don't consider their physical behaviors or their surrounding environment (Hendrickson and Rehak, 1993; Naji, 1997; and Wakefield, 1999).

However, the structure of a construction system that includes the objects' physical behaviors and their corresponding geometrical representations is yet to be developed. On the other hand, the development of such system is necessary to improve modeling of the construction operations (Hendrickson and Rehak, 1993).

Furthermore, each modeling and simulation tool in construction uses its own classification structure and language. There is no common construction language that can be effectively used across the construction domain to model, analyze, and capture construction operations. The development of a common language is an essential foundation for improvement in construction.

To potentially improve the over all construction processes, we need to better understand what construction operations are, how to represent and model construction operations, how do the construction product and processes interact with each other, and develop a system (a common construction language) that allows us to model construction operations taking into account their environments, geometric representations, and physical behaviors.

1.3 OBJECTIVE

The main goal of this research is to develop a new system for modeling and simulating construction operations. This system will potentially provide the participants in the process with an opportunity to better understand and analyze the construction operations involved in constructing a designed facility. The specific objectives to achieve this goal are identified as follows:

Firstly, the research will develop a common construction taxonomy that can be usefully utilized to capture the diverse elements and model the products and processes for major types of construction operations. The common construction taxonomy is and essential foundation for the development of a construction language. The construction language will be used to describe construction operations and processes and to provide the basis for developing a new construction modeling system

Secondly, the research will show the limitations of existing modeling systems and the potential uses of virtual and physically-based modeling techniques to enhance modeling and simulation of construction operations. Virtual modeling provide the foundation to enable virtual construction of facilities before the actual construction takes place, where physically-based modeling has the potential to simulate construction processes, as if they were in “real” life.

1.4 METHODOLOGY

This research introduces a new taxonomy that can be used to model, analyze, and capture construction operations at several levels of detail. The taxonomy integrates knowledge of design processes and products, construction processes, virtual modeling, physically-based modeling, and construction modeling into one system. The developed taxonomy is essential for increasing the understanding of construction processes and operations.

The following steps identify the methodology utilized by this research to achieve the research objectives:

A) Identification of research knowledge.

The first step of the research methodology involves identification of the major types of knowledge and key research needs to assist in developing common taxonomy. The construction modeling environment requires three major categories of knowledge identified as follows:

1. Knowledge of construction operations representations. This category of knowledge involves analyzing construction operations at several levels of detail. The objective of this analysis is to identify which operations can be usefully modeled and the appropriate level of the model. Previous research (Everett, 1991) determined that all construction operations could be categorized into 12 basic tasks. Everett (1994) describes the "basic tasks as the fundamental building blocks of construction field work, each representing a series of steps that comprise an activity."

2. Knowledge of construction objects representations. The focus of this knowledge is on the development of a breakdown structure of the construction objects involved in performing any operation. Modeling such processes is difficult because of the complex nature of the relationships between the different components involved in a given project (Opdenbosch, 1994). In addition, these relationships need to be translated into a simpler visual construction-oriented language to simplify the modeling process. Using an object-oriented approach will help to divide a complex project into its major elements. These elements can be further divided until they are simple enough to be modeled (Opdenbosch, 1994). By breaking down the construction project into components and sub-components and defining these

components as objects that interact with each other and the user, the simulation and modeling processes become easier and more effective.

3. Knowledge of physical behaviors and geometrical representations of objects. The third area of knowledge concentrates on incorporating the physical behaviors of the objects with their corresponding geometric representations. In addition to the geometric representations and attributes of the objects (i.e., equipment, material, and building components), this area investigates the potential use of a variety of physically-based (i.e., rigid body dynamics) modeling techniques and virtual modeling to improve the realism and accuracy of their representations and behaviors. For example, the objects should not pass through each other and they should move as expected when pushed, pulled, or lifted. By introducing the physics and virtual modeling, we can get one step closer to mimicking the ways of doing construction in "real" world.

As shown in Figure 1.3, the identified areas of knowledge form the backbone structure of the proposed construction modeling environment.

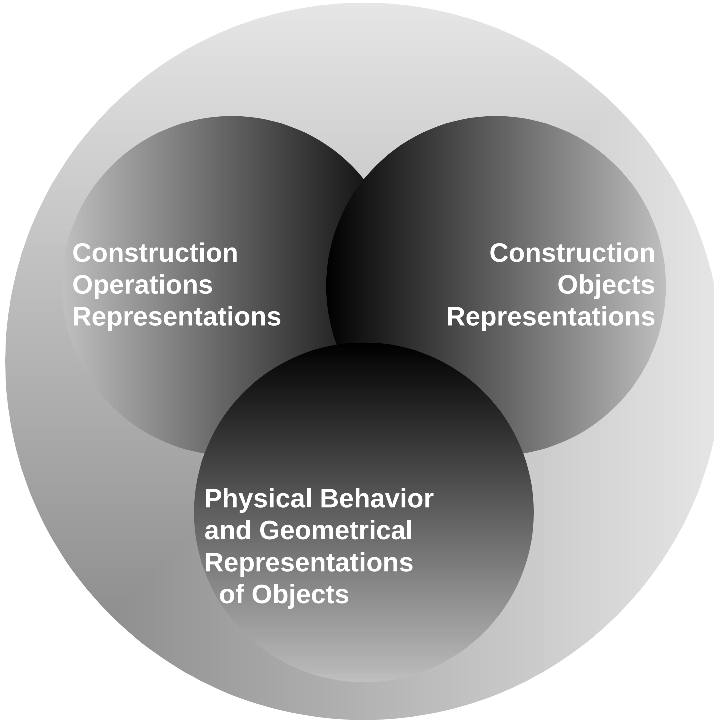


Figure 1.3: Major elements of the construction modeling environment.

B) Review of existing systems.

Review of existing modeling and simulation systems, physically-based modeling, virtual modeling, information modeling, and construction work classification methods to determine the current level of development and to identify opportunities for improvement.

C) Taxonomy development.

Development of a new taxonomy for modeling construction operations by expanding on existing classification systems and by proposing a new approach that deals with the complexity of construction operations models.

D) Examination and validation.

Action research is utilized as the main method to evaluate, improve, and validate by example the developed taxonomy. The methodology used to evaluate, improve, and validate the developed taxonomy consists of the following steps:

1. Conduct pre-evaluation interviews with the participants.
2. Develop a common taxonomy for classifying construction operations.
3. Develop examples, re-evaluate, and improve the modeling system.
4. Conduct post-evaluation interviews with the participants.
5. Incorporate comments and improve upon the developed taxonomy.
6. Draw conclusions; identify areas of improvements, and potential research extension.

1.5 CONTRIBUTION

This research starts with acknowledging the fact that a common construction language do not exist or not widely used for representing construction products and processes which is a major barrier to realizing the full potential of improving construction operations. However, progress has been made. The first major contribution of this research has been from the beginning on diminishing this barrier and enhancing construction processes knowledge and modeling techniques by developing a new common taxonomy for modeling construction operations. The taxonomy provides a structured construction language that can be usefully utilized to model, analyze, record, and potentially improve construction operations.

The second major contribution of this research is identifying the major types of construction knowledge that are required to increase the understanding of construction products and processes integration. The major types of knowledge include knowledge of process breakdown structure, knowledge of product breakdown structure, knowledge of resources, knowledge of construction processes, knowledge of physical and information inputs. Further understanding of these types of knowledge provides a major opportunity for using the developed taxonomy in performing the following activities: analyze and record construction operations in a useful way for future improvements, evaluate and select construction methods, identify input to products designs by analyzing and selecting construction sequences and methods, and shorten the construction schedule by identifying opportunities for prefabrications, pre-assembly, and modularization.

This research also provides the required guidelines for developing a virtual modeling environment that takes into accounts the geometric representations and physical behaviors of the components and the processes involved in shaping the product.

1.6 LIMITATIONS

The focus of this research is on the development of a modeling system and common taxonomy for modeling construction operations. Therefore, the limitations of this research are as follows:

1. The intent of this research is not to create a new virtual modeling environment, but to show the potential benefits in utilizing virtual environments to improve modeling of construction operations and to identify the requirement for a new construction-modeling environment. Therefore, existing modeling and simulation systems were employed during the course of this research to test and validate the developed taxonomy.

2. The development and validation of the physically-based models considered here require a long time. However, similar to the standard component representations of CAD models, once the basic physical models are formulated, one can use them in many construction applications (Hendrickson and Rehak, 1993). Therefore, the focus of this research is on investigating physically-based modeling techniques and their potential uses in modeling construction operations. Physically-based modeling approach is an integral part of the developed taxonomy and the development of such models is an area that requires further research and development.

1.7 POTENTIAL OUTCOME

The developed taxonomy has the potential to improve construction research in many areas. Potential research areas such as: 1) productivity improvement; 2) assemblage and constructability; 3) selection of construction means and methods; 4) maintenance techniques; 5) construction automation; and 6) capturing the knowledge of field personnel for teaching and learning purposes.

1. Improve productivity. The ability to record and model construction operations in useful way will help in setting the needed foundation to measure productivity in the construction industry. Due to the complex nature of the construction industry it is difficult to measure productivity. Several reports and statistical studies failed to explain productivity changes in various industry sectors or geographical areas (Cremeans, 1981; Everett, 1991). “Productivity is generally perceived to be a major problem in construction” (Everett, 1991).
2. Constructability of the designed facilities can be evaluated before actual construction.
3. Selection of construction means and methods to enable better engineering decisions throughout the design and construction processes and to answer questions such as: What is the time needed to construct a facility? What are the cost consequences of choosing this particular design? And what is the most appropriate method to build a designed facility?
4. Maintenance techniques can be improved by providing adequate access, safety, and field of view.
5. Construction automation. The proposed taxonomy will help in identifying automation opportunities in construction and show the feasibility of developing and implementing such opportunities in the construction industry.
6. Knowledge of field personnel can be captured for teaching and learning purposes. The taxonomy can be used to record construction operations.

1.8 THESIS ORGANIZATION

This dissertation is divided into nine chapters. In Chapter One, a brief outline is provided for research presented in this dissertation. The research problem is described. The research methodology, limitation, contribution and potential outcomes are presented.

Chapter Two provides insight on construction modeling and simulation systems. Several modeling and simulation techniques used in modeling construction operations are described. Simulation and visual animation examples of a concrete slab pouring operations are provided.

Chapter Three defines physically-based modeling techniques and their potential uses to enhance modeling of construction operations. The concept of physically-based prototype libraries is introduced. Examples of physically-based simulators are given from previous research efforts.

Chapter Four concentrates on the fundamentals of virtual modeling and 4D-CAD modeling approaches. The benefits and limitations of virtual modeling and 4D-CAD approaches are identified.

Chapter Five describes the potential use of robotics and automation opportunities in construction. The distribution of work between human, tools, and equipment based on their physical and information contribution is discussed.

Chapter Six describes and analyzes classifications of construction work at several levels of detail. The analyses are focused on identifying the construction operations that can be usefully modeled and the appropriate level of the model. Process and product breakdown structures are described.

Chapter Seven describes the developed taxonomy for modeling construction operations. A complete description of each of the taxonometric levels is provided. The developed taxonomy is mapped to one of the state-of-art information modeling system, industry foundation classes, to identify the benefits of the developed taxonomy and show the limitations of existing information modeling systems. Areas of potential concurrency between the design process and taxonometric structure are identified. The adaptability of the developed modeling system to approaches such as design for disassembly is discussed and examples were presented.

Chapter Eight illustrates and validates by examples the potential uses of the developed taxonomy to model and improve construction operations. Examples of steel structures fabrication, assembly, and erection are provided for validation.

Chapter Nine includes a summary of the research presented in this dissertation, as well as some possible directions for future research and extensions to the ideas in this research are identified.

CHAPTER TWO: MODELING CONSTRUCTION OPERATIONS

2.1 INTRODUCTION

Simulation and modeling is a very promising tool for analyzing construction operations. This chapter reviews general modeling and simulation systems that have been introduced to the simulation and modeling community. Also, this chapter provides and overview of the current state of the simulation techniques and their potential use for modeling construction operations.

In daily construction practice, construction designers make decisions regarding complex construction processes. These decisions include construction methods, selecting equipment, and planning operations. In some situations, decisions are made with unexpected outcomes. This is because of the complexity of the operations or the difficulty in visualizing all the processes involved. In real life, testing a construction method is very expensive and time consuming. However, simulation is a convenient technique to model "real-life" construction operations.

2.2 GENERAL MODELING AND SIMULATION SYSTEMS

General modeling and simulation systems are commonly used in manufacturing and other industries. The use of general modeling and simulation languages in construction are demonstrated with models for equipment selection (Teicholz, 1963), for the estimation of project durations (Carr, 1979), and for the evaluation of resource allocation strategies (Moura, 1986).

Simulation systems can adopt one of several approaches or strategies. Three simulation strategies are commonly recognized: event scheduling (ES), activity scanning (AS), and process interaction (PI) (Martinez, 1996). In manufacturing and other industries, the PI strategy combined with ES or AS is very effective in modeling systems because entities that move have many attributes that differentiate them; and the machines or resources that serve the entities have a few attributes, and don't interact too much. Examples of general modeling and simulation systems are Petri Nets, GPSS, HOCUS, SIMAN, Q-GERT, SIMSCRIPT, SIGMA, ithink, and SLAMII (Damrianant, 1998).

2.2.1 GPSS

GPSS (General Purpose Simulation System) is a simulation modeling language that was developed in the early 1960's by IBM. GPSS is oriented toward queuing systems. A GPSS simulation consists of temporary transactions and permanent facilities, which flow around a network of block diagrams. These transactions are created and destroyed as the simulation proceeds and which move through various GPSS blocks. There are about 40 standard building blocks in GPSS. Facilities are used to represent the resources needed by the transactions at the nodes of the network (Damrianant, 1998). The most recent version of GPSS is GPSS/World (Schriber, 1994).

GPSS/World employs a set of new GPSS Blocks and commands, which support input/output, rescheduling, continuous and mixed modeling and multiple data types that include integer, real, and string objects. Also, GPSS World includes an embedded programming language called PLUS. PLUS language consists of only a few statement types that can be used just about anywhere within the simulation, including GPSS Blocks. This feature improved the flow of simulations. Several new GPSS Blocks have been added to GPSS World. The new blocks such as, OPEN, CLOSE, READ, WRITE, and SEEK Blocks provided a powerful interface to programs written in other languages.

2.2.2 HOCUS

HOCUS (Hand Or Computer Universal Simulator) (Hills, 1971), developed in the early 1960's, enhanced and popularized the concept of activity cycle diagrams. A HOCUS activity cycle diagram consists of two kinds of nodes: queues (circles) and activities (boxes) connected by arrows. HOCUS could be used for both discrete and continuous process modeling. It has been used for numerous large-scale simulations in several industries in Europe (Poole and Szymankiewicz, 1977).

2.2.3 ITHINK

ithink is a commercial computational package that has been developed for modeling system dynamics. ithink provides friendly user interface and animation and it can be used to model discrete systems, such as in construction (Paulson, 1985). However, its modeling methodology is difficult to use and understand when it comes to modeling discrete systems (Damrianant, 1998).

2.2.4 SLAMII

SLAM (Simulation Language for Alternative Modeling) was developed in 1979 as a commercial simulation language (Schriber, 1994). SLAMII was designed in 1981 as an enhancement to SLAM. SLAM and SLAMII allow modeling in a network form. SLAMII is a high-level simulation language with FORTRAN and C versions that can model complicated applications. SLAMII network models can be built, animated, and run by using another computer program named SLAMSYSTEM.

2.3 CONSTRUCTION SIMULATION USING NETWORKS

All construction process simulation tools are based on activity cyclic diagrams (ACDs) and on activity scanning (AS) simulation strategies. For the past two decades, researchers have recognized the need to use computer simulation to plan and analyze construction operations and activities. Consequently, research in construction simulation and modeling has been actively carried out, especially in academia.

2.3.1 CYCLONE (CYCLIC OPERATIONS NETWORK)

One of the first and best known simulation languages specifically designed to investigate the use of simulation networks for modeling construction operations and activities is CYCLONE (Cyclic Operations Network) (Halpin, 1973, 1977). The CYCLONE system has been used frequently to model construction processes. This frequent use is due to the ability to provide a quantitative way of viewing, planning, analyzing, and controlling the processes and operations (Halpin and Riggs, 1992). It has been successfully used in modeling construction processes such as concrete batch plant (Lluch and Halpin, 1982), tunneling (Touran and Asai, 1987), and modeling construction resources and resolving construction disputes (AbouRizk et al., 1992, and AbouRizk and Mohamed, 2000).

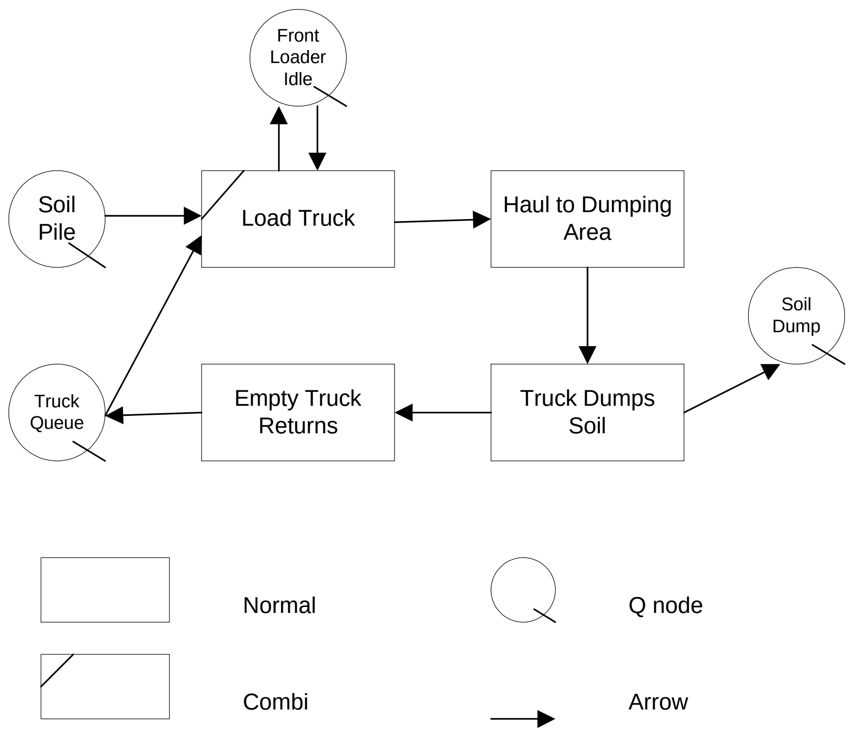


Figure 2.1: CYCLONE network for modeling earth-moving operations.

As shown in Figure 2.1, CYCLONE uses the following four basic modeling elements to develop a graphical modeling network of any construction operation (Halpin and Riggs, 1992):

Normal: The normal work task modeling element, which is unconstrained in its starting logic, indicates active processing of (or by) resource entities. Activity nodes represent activities that may be executed whenever any of the required resources is available

Combi: The constrained work task modeling element, which is logically constrained in the starting logic but otherwise, is similar to the normal work task modeling element.

Queue: The idle state of a resource entity symbolically representing a queuing up or waiting for use of passive state of resources. Nodes represent places where labor, equipment, or materials wait before being used by an activity.

Arrows: Represent the resource entity directional flow modeling element.

In addition to the above elements, CYCLONE networks may include function elements and counter elements. Function element is a special element that is used to consolidate or multiply flow units. A counter element is a special element that is used to measure productivity of the system. It is also used to control the number of times a modeled system cycles before its completion.

MicroCYCLONE is a microcomputer-based program designed to run CYCLONE simulation models. Before running the simulation, the graphical model network should be converted into a numerical model using a specialized POL (Problem-Oriented Language).

Many researchers have used CYCLONE as a base to build their simulation systems such as Insight (Paulson et al., 1987), UM-CYCLONE (Ioannou, 1989), Micro-CYCLONE (Lluch and Halpin, 1982), and STROBOSCOPE (Martinez, 1996).

2.3.2 RESQUE

RESQUE is an acronym for RESource based QUEuing network simulation system (Chang, 1986). RESQUE was designed as a significant enhancement to CYCLONE, where the model is not limited to the information conveyed by the network.

2.3.3 COOPS

COOPS is an acronym for Construction Object Oriented Process Simulation system (Liu, 1991). It is an extension and enhancement to CYCLONE that was designed and implemented using an object oriented programming language.

2.3.4 CIPROS

CIPROS is an acronym for Construction Integrated PROject and process planning Simulation system (Tommelein et al., 1994). CIPROS is both a process level and a project planning tool. It contains an expandable knowledge base of construction techniques and methods and makes extensive use of hierarchical object-oriented representation of resources and their properties.

2.3.5 STROBOSCOPE

Stroboscope (State and ResOurce Based Simulation of Construction ProcEsses) is a general-purpose simulation programming language specifically designed to model construction operations (Martinez, 1996). It is based on activity cycle diagrams (ACDs) and the activity scanning (AS) simulation paradigm.

Stroboscope modeling elements have attributes, defined through programming statements, which define how they behave throughout a simulation. Resources in Stroboscope can be bulk or discrete, depending on their type. Bulk resources represent entities that are not individual and cannot be uniquely identified, such as sand, water, etc. Discrete resources represent unique individual entities, such as a specific truck, particular concrete block, etc.

What mainly differentiate Stroboscope from other simulation tools resides in its simulation language and its open design. Its simulation language represents resources as objects that have assignable, persistent, and dynamic properties and can actively and dynamically take into consideration the state of the simulation process (Martinez, 1996). Stroboscope's open design allows the user to determine the input and output at two levels. The first level uses Stroboscope's built-in programmability language. The second level extends Stroboscope through dynamic link libraries created with high level languages: C and C++ (Martinez, 1996).

Stroboscope includes an optional Graphical User Interface (GUI) hosted under Visio 3.0 or later version. Stroboscope also has some of the characteristics that general-purpose programming languages have such as, built-in logarithmic and trigonometric functions, conventional variables and arrays, and structured flow control with if-elseif-else-endif blocks.

2.3.6 MODELING EXAMPLE UTILIZING STROBOSCOPE

A concrete slab pouring operation was selected as the case study and the Stroboscope simulation package was used as the primary simulation environment tool. Concrete slab placement is common and straightforward in construction. However, detailed descriptions of the required processes, available resources and restrictions were examined prior to the development of the simulation models as follow: the placement operation uses ten cubic meters transit mix trucks to deliver concrete to the site from a batching plant. The ready mix trucks are loaded one at a time at the batching plant in 5 minutes. They travel back to the site in 8 minutes and there unload their concrete to a hoist. The hoist takes two cubic meters of concrete at a time. This means that in order to completely empty a truck, the hoist must be filled five times. It takes two minutes to fill the hoist. When a truck is empty it travels to the batch plant in seven minutes and then waits to be loaded again.

Once the hoist is filled with concrete at the ground floor, it hoists up to the slab being poured in one and half minutes. There it waits until a two cubic meters concrete hopper is empty and then fills the hopper in two and half minutes. The hoist then goes down to the ground floor in one minute where it waits to receive another two cubic meters of concrete from a truck.

The hopper can fill any number of empty quarter-cubic meters buggies in half a minute each. This means that a full hopper fills eight buggies before it becomes empty. A concrete placement crew picks up a loaded buggy, empties the concrete onto the slab and returns the empty buggy in one minute.

There are two ready mix trucks, one hoist, one hopper, four buggies and one concrete placement crew. The volume of concrete to be poured is seventy cubic meters.

This example was modeled using three different schemes and represented different levels of modeling flexibility and complexity. The first model utilized Stroboscope programmability language, while the second model employed EZStrobe graphical user interface, and the third model used Proof animation.

The first model was developed in Stroboscope, the advanced and programmable simulation system. This model took the longest time to develop compared to the same model developed in EZStrobe. The developer had to define the resource types, network nodes, network links, and all the simulation constraints that control the simulation in an ASCII-like simulation code. Subsequently, the simulation code was debugged for errors before its execution with Stroboscope simulation engine. Then the process of debugging and running the simulation if repeated over and over again until the final the model is produced. The following code is extracted from the simulation code for concrete placement operation.

```
/* Definition of resource types
.
.
VARIABLE nTruck 2;
VARIABLE nBuggy 6;
.
.
GENTYPE         Batch; /BA
COMPTYPE   Buggy; /BU
GENTYPE         Concret; /CO
GENTYPE         Crew; /CR
.
.
/* Definition of network nodes
.
.
COMBI           TrkLoads;
NORMAL          TrkBack;
COMBI           FillHoist;
.
.
/* Definition of network Links
.
.
LINK            TR6 SpaceInTrk TrkTravel;
LINK            TL7 TrkTravel TrkWtPlnt;
LINK            TL1 TrkWtPlnt TrkLoads;
.
.
/* Startup of TrkLoads
.
DURATION        TrkLoads '5';
..

/* Termination of PlaceConc

RELEASEAMT      BF4 '1';
RELEASEAMT      CP2 '1';
.
.
SIMULATEUNTIL PlaceConc.TotInst>=280;
```

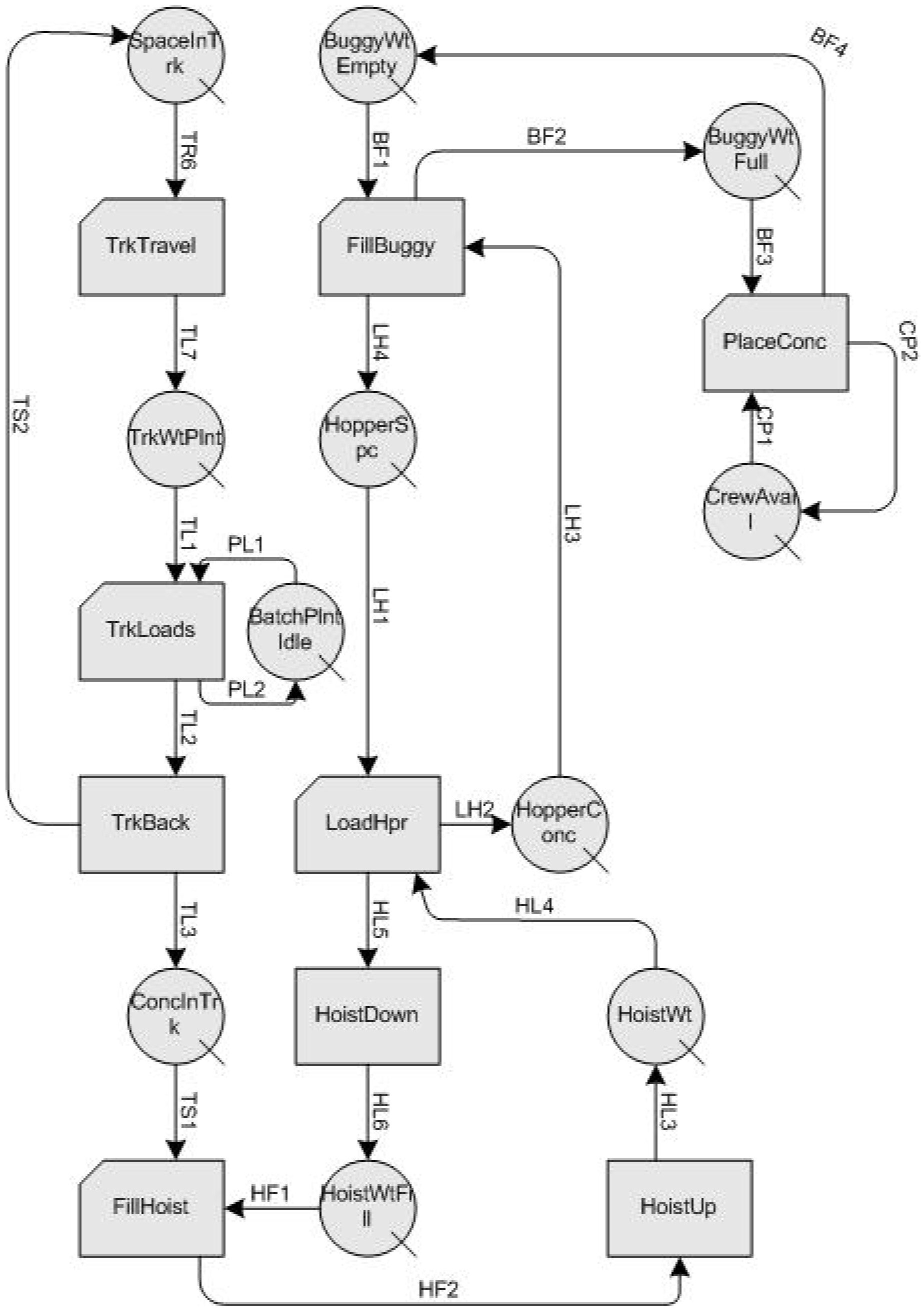


Figure 2.2: EZStrobe network for model of concrete slab placement.

As shown in Figure 2.2, the concrete placement operation was modeled with the Stroboscope's graphical user interface EZStrobe. EZStrobe substitutes the need to write the simulation code in an ASCII-like format with a friendly, objects drag and drop, user interface hosted under Microsoft Visio.

The third model was developed with Proof animation and Stroboscope. Proof animation is a playback animation tool consists of two paired files. The first file, called the layout file, is similar to a CAD-like drawing tool. It contains drawings, classes from which objects can be created, and paths. Paths are fixed route through which objects can move at certain speed.

The second file, called animation trace file, is produced by Stroboscope simulation model. The trace file is a time-ordered sequence of commands that controls the dynamic behavior of the animation. Each command specifies and event which alters the state of the animation. For example, *CREATE truck truck1* command is used to create object *TRUCK1*. *A PLACE TRUCK1 on truckmv* command places the new object on the *truckmv* path, and *SET OBJECT truck1 TRAVEL 8.000000* commands specifies the object's speed. For example the following trace code was extracted from the source file generated by Stroboscope.

```
CREATE truck truck1
CREATE truck truck2
CREATE buggy buggy1
CREATE buggy buggy2
CREATE buggy buggy3
CREATE buggy buggy4
CREATE hoist hoist
TIME 5.000000
PLACE truck1 ON truckmv
SET OBJECT truck1 TRAVEL 8.000000
TIME 10.000000
PLACE truck2 ON truckmv
SET OBJECT truck2 TRAVEL 8.000000
TIME 15.000000
```

PLACE hoist ON hoistup
.
.
.
TIME 194.500000
PLACE buggy4 ON buggygo
SET OBJECT buggy4 TRAVEL 0.250000
TIME 194.750000
PLACE buggy4 ON buggybc4
SET OBJECT buggy4 TRAVEL 0.250000
TIME 195.500000

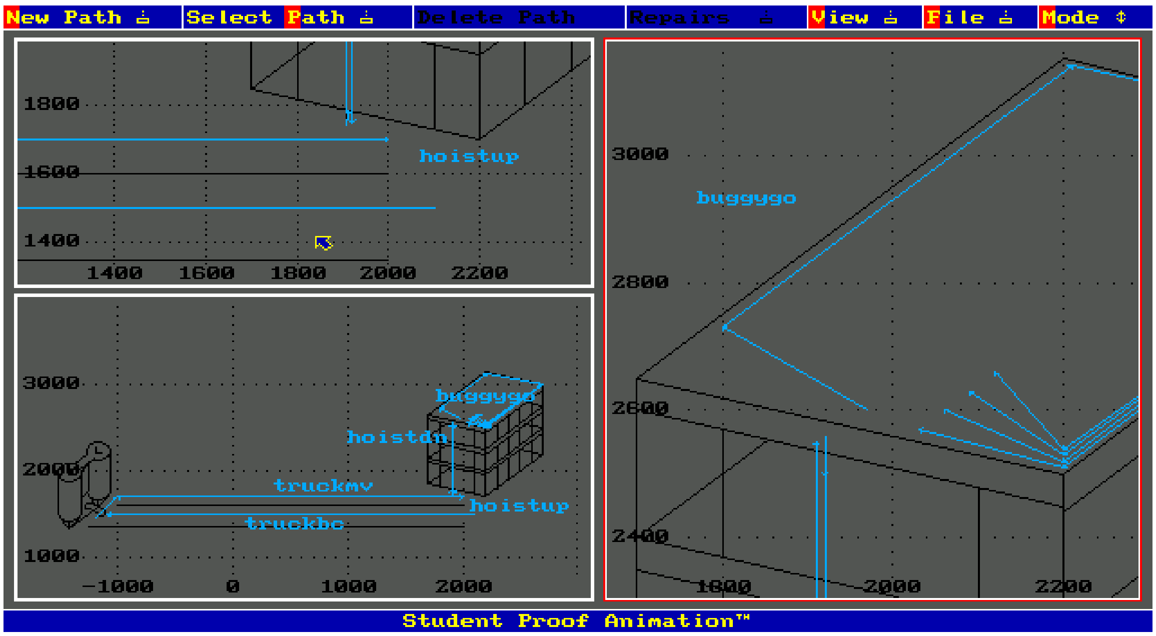


Figure 2.3: Proof animation layout and paths of concrete placement operation.

As illustrated in Figure 2.3, the layout and paths were created using Proof's CAD-like drawing tools. Paths such as *truckmv, truckbc hoistdn, hoistup and buggygo* are fixed routes, which objects follows, while the simulation is running.

This animation shows the batch plant, ready mix-trucks, hoist, buggies and roads (see Figure 2.4). Furthermore, while the simulation if running, it shows the many instances in which Proof is used to animate a concrete placement operation. Animations were used to simply illustrate and verify the results of the simulation model.

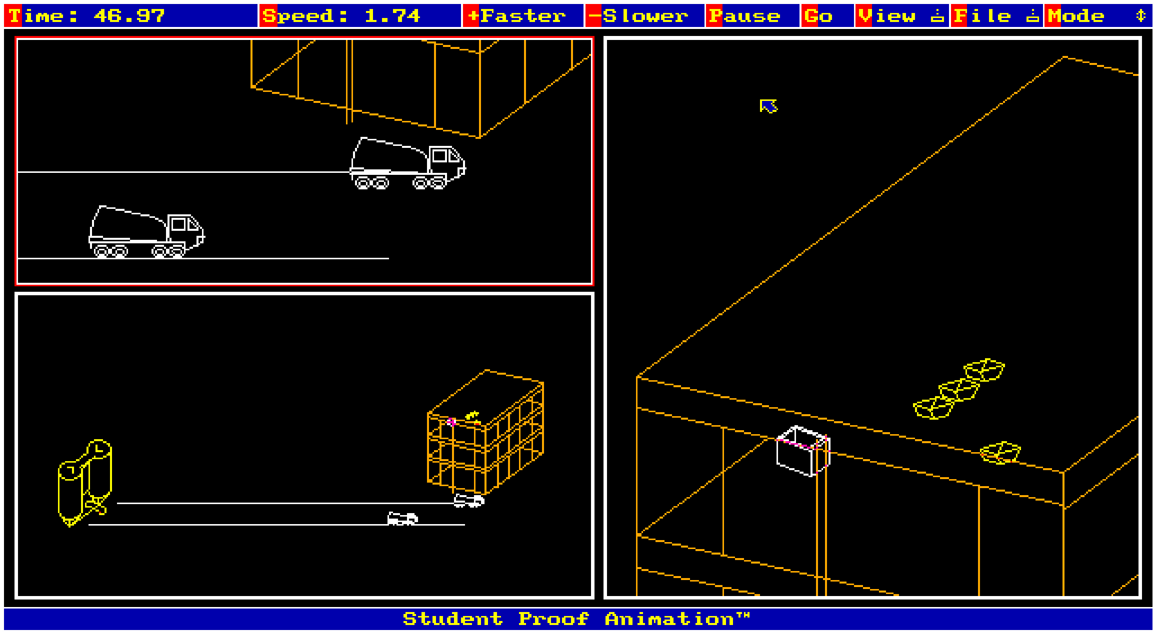


Figure 2.4: Proof animation of concrete placement operation.

2.4 SYNOPSIS

In this chapter, general modeling and simulation systems that are popular in the construction community are described. Also, an overview of the current state of modeling and simulation techniques is presented. . Concrete placement operations were modeled in three different simulation tools: the first model utilized Stroboscope's programmability language, while the second model employed EZStrobe graphical user interface, and the third model used Proof animation.

CHAPTER THREE: PHYSICALLY-BASED MODELING

3.1 INTRODUCTION

This chapter provides an understanding of physically-based modeling techniques and their connections to the developed taxonomy. Due to the limited existing literature on application of physically-based modeling techniques in construction modeling, this chapter reviews applications from other fields, such as mechanical engineering, industrial engineering, and computer graphics. Additionally, this review shows the advantages of physically-based modeling techniques and their potential uses to improve construction modeling applications.

In the past few years, physically-based modeling techniques have demonstrated that more attractive and realistic-seeming motion can be created by subjecting objects to forces and constraints and making the objects move as they would in physical environment (Skolnick, 1990, Beliveau et al, 1993, and Park, 2002).

3.2 WHAT IS PHYSICALLY-BASED MODELING?

What is physically-based modeling? Physically-based modeling is a relatively new field that focuses on developing methods that enable people to specify, design, control, and build computational models of heterogeneous physical systems of objects. Barzel (1992) defined physically-based modeling as modeling that incorporates physical characteristics into models, allowing numerical simulation of their behavior. In addition, Park (2002) defined a physically-based virtual reality simulator as a system of computer programs and interfacing devices that receives users' input in real-time interactive mode, performs calculations for the response of physical things based on their representations, and provides the result in 3D graphical objects in real-time.

The aim of physically-based modeling is to translate and transfer natural phenomena to a computer program. There are two basic steps in this process: mathematical modeling and numerical solution. The mathematical modeling is concerned with the description of the natural phenomena through mathematical equations. Differential equations that govern the dynamics and geometric representations of the objects are the typical ingredients of the mathematical model. Since the natural phenomena are generally very complex, the modeling process typically involves and requires considerable simplification. The numerical solution involves computing an efficient and accurate solution of the mathematical equations.

3.3 BENEFITS OF PHYSICALLY-BASED MODELING

Why physically-based modeling? There are many advantages to the implementation of physically-based modeling as an integral component of the developed taxonomy. These advantages can be listed but not limited to the following:

- Physically-based modeling facilitates the creation of models capable of automatically synthesizing complex shapes and realistic motion.
- It adds new level of representation to graphics objects. In addition to geometry, forces, torques, strain, mass, pressure, momentum, velocities, accelerations kinetic and other physical quantities are used to control the creation and evolution of models.
- Physically-based models are responsive to one another and to the simulated physical environment that they inhabit.

3.4 PHYSICALLY-BASED MODELING AND THE DEVELOPED TAXONOMY

The methodology of incorporating physically-based modeling in the developed taxonomy for construction-based modeling environment is somewhat similar to EON and Deneb modeling systems. Both EON and Deneb are integrated environments for development of interactive 3D real-time simulation that incorporates the latest physically-based modeling techniques. Objects in EON and Deneb simulations receive physical behaviors such as weight and center of gravity. Physical forces affect their velocity, acceleration, and rotation.

The idea is to produce a tool where most programming is done in a visual manner, by combining small intelligent objects. By connecting existing small intelligent objects to one another, new and more complicated objects can be formed. These newly formed objects can then be transformed into new prototypes to be used in other applications. In this context, intelligent objects are objects that will behave in a real manner according to the physical laws.

The development and validation of the physical models requires a large amount of developer's time. However, the research objective is to introduce an overall framework and to show the effectiveness of applying physically-based modeling in the development of a construction-based modeling system. Thus, this research reviews already developed concepts in physically-based modeling. Prototype libraries of physically-based modeling can be usefully integrated within the developed construction-based Environment. Yet, some specific construction tasks (i.e., the crane control system) might involve more complex systems beyond the capacity of the physical prototype libraries. Such systems require development of a specific task-based physically-based modeling.

3.5 PHYSICALLY-BASED SIMULATORS

Research efforts involving physically-based models and construction have been related to the development of virtual physically-based equipment simulators. Illustrated examples were presented by Cheok and Beck (1996), Wakefield et al. (1996), and Park (2002). These efforts concentrated on the development of the architecture and pipeline of VR simulator. In general, they all agree on the same architecture as shown in Figure 3.1.

As shown in Figure 3.1, the VR simulator architecture is composed of three components as follows: computational component, graphical component, and interactive user interface. While the computational component includes physically-based models of the simulated machine and its environment, the graphical component includes the geometrical representation and the rendering engine.

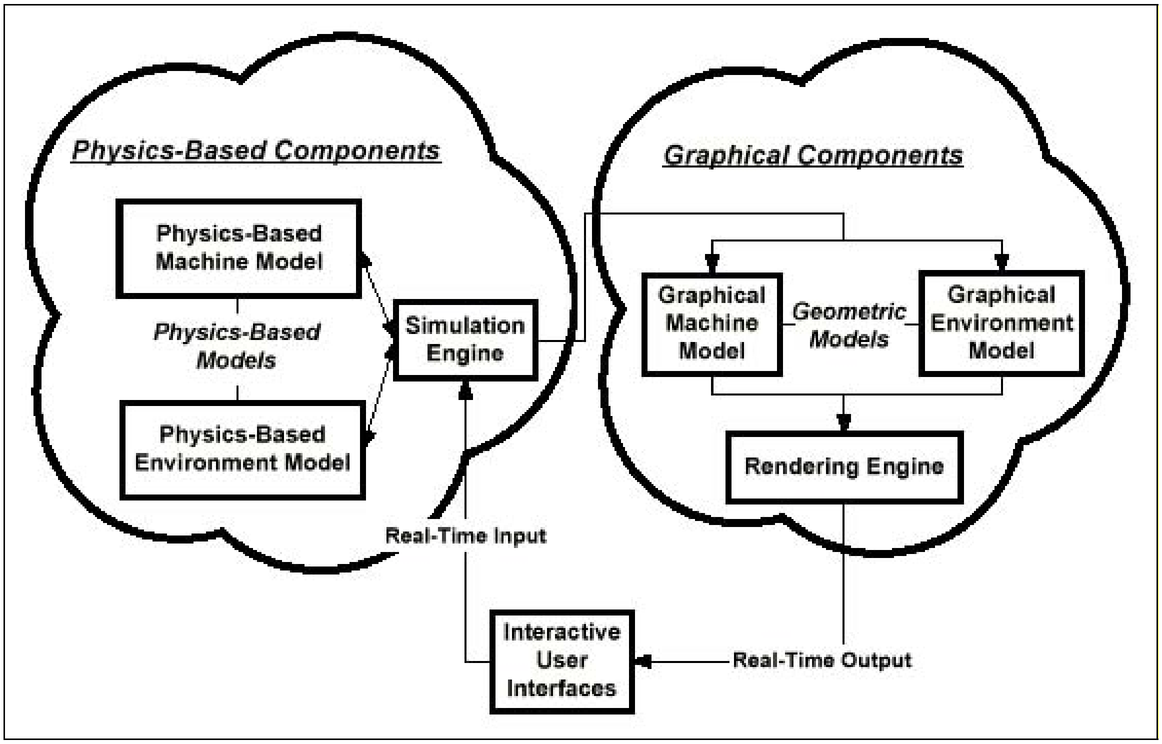


Figure 3.1: Architecture and pipeline of virtual reality simulator system (Park, 2002).

The physically-based models encompass the mathematical representation of the simulated machine and its surrounding environment and describe their behaviors according to the physical laws such as statics, dynamics, etc. The physically-based model describes the parts and components of the simulated machine and determines how the machine behaves on an operator's commands. On the other hand, the physically-based model includes representations of physical objects that physically affect or interact with the simulated machine. Thus, the simulation engine plays the role of communicator between the two models and translates their response to the downstream graphical component.

The graphical models cover the graphical and the three dimensional geometric representations of the machine and the environment. The graphical models stored and update the geometric data of the machine and the environment based on the information for the simulation engine. Accordingly, the rendering engine compiles the geometric data and interprets it in 3D rendered images format.

The last component is the real-time user interface, where the users can interact with the simulated machine and the environment through several user input/output interfaces. User interface includes but not limited to joysticks, control levers, handles, monitors, HMD (head-mounted display), etc.

3.5.1 PHYSCIALLY-BASED SIMULATORS EXAMPLES

Li (1993) developed a real-time computer graphics simulator with physically-based modeling techniques to model soil properties and behaviors in virtual environments. The physically-based model was based on analytical methods and Newton's laws of physics. Thus objects will behave in a realistic manner under external forces. Along with the physically-based models, a real-time graphics model for soil slippage and manipulation was presented to simulate excavating activities in dynamic terrain. The environment allows the user to dig ditches, leave tracks, produce bomb craters, pile up dirt, and push down buildings. The developed simulator provided convincing animation of soil movement using physically-based soil particle model; however, it didn't address the interaction between the soil model and the excavator model.

On the other hand, Wakefield et al. (1996) developed a real time interactive VR excavator simulator, which is capable of integrating the physically-based information of an excavator into a simulated graphical scene. Figure 3.2 depicts the architecture and the major components of the developed simulator. It mainly consisted of the operator controls, the excavator model, graphics model, and the mathematical model. The mathematical model represented the precise parts and structures of a real excavator, which in turn provided the graphical model with a ‘real’ physically-based interactive response to the users input actions.

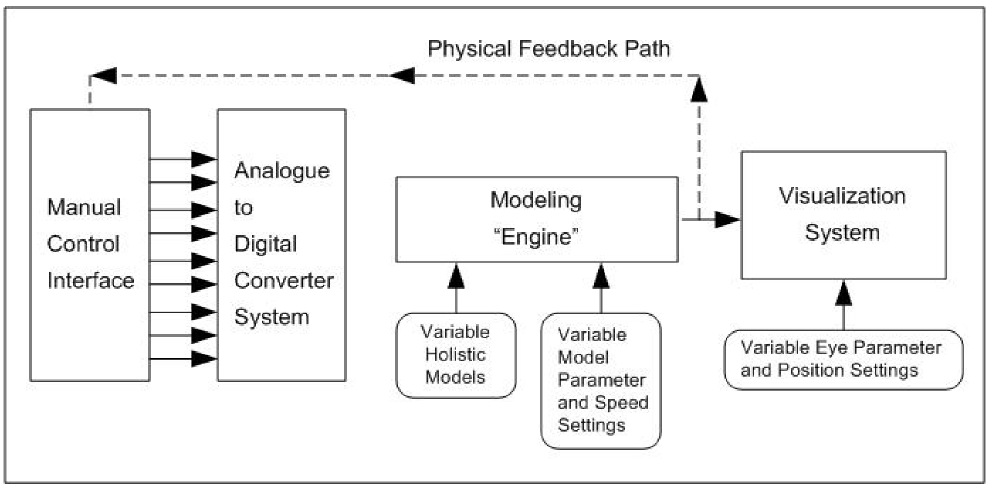


Figure 3.2: The architecture and pipeline of Wakefield and O’Brien VR excavator simulator (Wakefield et al., 1996).

Following the path of Wakefield, Park (2002) proposed a complementary mathematical model of excavator digging and calculation methodology. The mathematical model provided a physically-based soil-bucket interaction data to a simulator. The calculation methodology provided systematic and efficient methods to ensure the seamless integration of the excavator digging model with a VR simulator system. As a result, the simulator is realized as an engineering process tool equipped with real-time interactivity. The functional components are depicted in Figure 3.3.

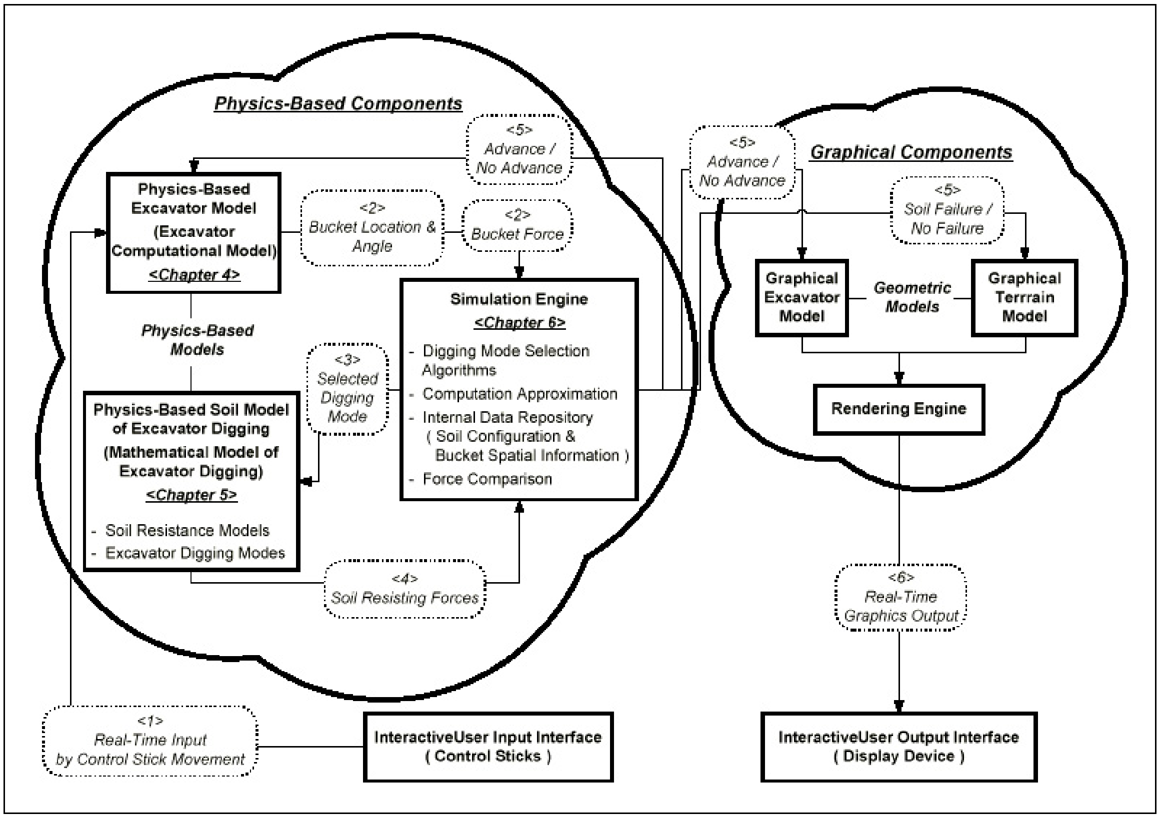


Figure 3.3: Park's proposed architecture and pipeline of virtual reality simulator system (Park, 2002).

3.6 PHYSICALLY-BASED SIMULATION IN MECHANICAL SYSTEMS DESIGN

The approach to model and analyze real-world behavior of dynamic mechanical systems using computer simulation is widely accepted among mechanical engineers. It has been used by Lockheed Martin Aeronautical Systems to solve a fatigue-related problem in the C5 airplane cargo door (CADSI, 1999). Another example is the research at Ruhr-University in Bochum to simulate and analyze the dynamic characteristics of child restraint systems in automobile crash tests (CADSI, 1999). ADAMS and DADS are two modeling and simulation systems that provide the capabilities to build 3D virtual prototypes with the same basic steps used in building physical prototypes (ADAMS

2002). These prototypes incorporate material properties such as mass, center of gravity, and moment of inertia. Figure 3.4 shows the steps and process involved in creating a generic simulation model from start to end.

For example, high-rise escalators have been designed based on static loads and torques determined from experiments. The physical experiments have a few drawbacks in that they are expensive, time consuming, and difficult to capture the dynamic operating condition of the escalator. To overcome these limitations, engineers at LG Industrial Systems in Changwon, Korea (CADSI, 1999) used computer simulation as an alternative approach in designing escalators. They used DADS, a simulation driven design software package from CADSI that enables engineers to model, simulate, visualize, and analyze real-world dynamic motions of 3D mechanical systems.

According to LG Industrial Systems (CADSI, 1999), the results obtained from the DADS simulation matches very closely the results of the corresponding physical model. Therefore, they used the computer simulation approach to improve the design process of the high-rise escalators.

ADAMS and DADS simulations provide the following advantages:

- The ability to examine the design in many ways.
- The ability to investigate design alternatives if the initial design is not satisfactory.
- The ability to adjust the design without the cost of building hardware prototype.

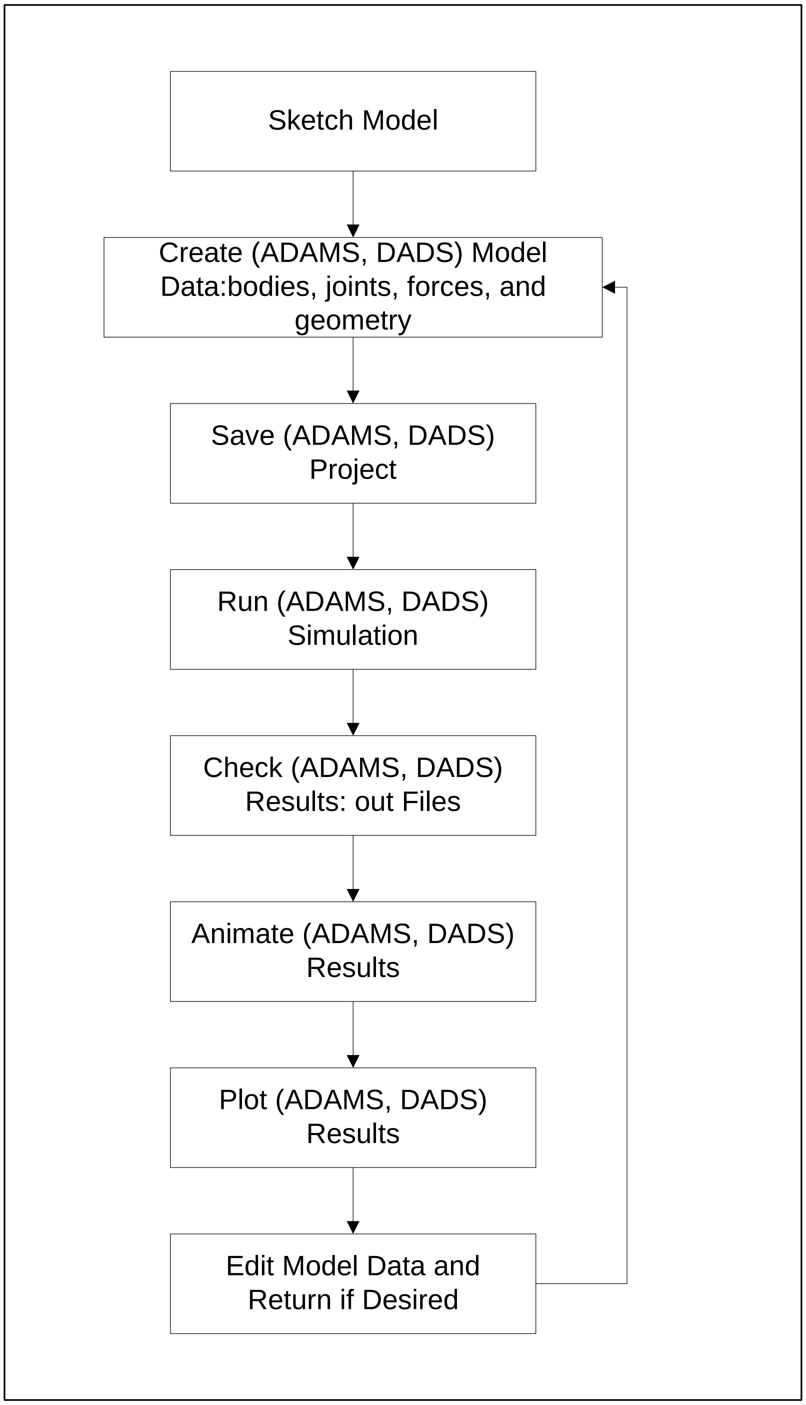


Figure 3.4: Process flow of system modeling and simulation in ADAMS & DADS (ADAMS, 2002).

3.7 PHYSICALLY-BASED MODELING IN INDUSTRIAL DESIGN SYSTEMS

Edwards and Luecke (1996) describe conceptually a physically-based modeling technique that can be used in a computer based design system. This technique uses finite element analysis with the B-spline basis functions to develop models of virtual components. The technique associates the dynamics characteristics with the graphical representations, of the virtual components, to provide realistic animated motions. Moreover, it provides capability to interact physically with the virtual components. “The inclusion of this type of model in a force feedback virtual environment will provide engineers with an intuitively simple system for constructing virtual models of prototype designs” (Edwards and Luecke, 1996).

3.8 PHYSICALLY-BASED PROTOTYPE LIBRARIES FOR RIGID-BODY MODELING

Barzel (1992) introduced a complete methodology for constructing prototype libraries of computer graphics routines for physical based-modeling. He examined closely what it means to construct a model of a real-world object and provided explicit means of describing and controlling such models and their behaviors. The objective of the prototype library is to serve as a general, reusable, and extensible library for rigid-body dynamics modeling. The library includes four modules with unique features. The library and the features embedded in the modules were used to describe the development of several physically-based models such as, a swinging chain model, and tennis ball cannon. The four modules in the prototype library are (Barzel, 1992):

- The coordinate frames module, which provides a common framework for working with 3D coordinates geometry.

- The kinematic rigid-bodies module, which defines the rigid-body motion (i.e., motion without regard to force or inertia).
- The dynamic rigid-bodies module, which provides classical Newtonian mechanics.
- The "fancy forces" module, which provides a mechanism to specify forces for the Newtonian model and support geometric constraints on bodies.

The prototype library includes the following features for rigid-body modeling (Barzel, 1992):

- Basic Newtonian motion of rigid bodies in response to forces and torques.
- The ability to measure the work done by each force and torque and balance it against the kinetic energy of the bodies.
- Support for various kinds of forces including dynamic constraints to allow constraint-based control.
- The ability to handle discontinuities in a model.
- The ability to be expanded, both by enhancing the existing modules and by adding additional modules.

Unlike conventional modeling techniques where models have only geometric properties, physically-based models have physical properties and their motion is subject to physical laws, such as Newton's second law of motion. In general, physically-based modeling combines the distinct steps which are modeling, rendering, and animation (Barzel, 1992).

3.9 EXAMPLE OF PHYSICALLY-BASED MODELING (RIGID BODY DYNAMICS)

A rigid body is an object with physical properties such as mass, center of mass and volume. It is neither flexible nor deformable. Integrating rigid body dynamics in 3D modeling environment enables 3D objects to move sensibly when influenced by a force such as gravitation.

EON simulation supports the idea of integrating rigid body dynamics into a 3D modeling environment. EON is a high performance toolkit for creating interactive, real-time 3D simulations. EON Users can define behaviors and interactions, as well as test simulations and change parameters, all in real-time (EON Reality, 2002). EON is a PC platform tool for enhancing the display of 3D objects, not for building the objects themselves. Objects in EON simulation receive physical behaviors such as weight and center of gravity, where their velocity, acceleration, and rotation are affected by physical forces.

As shown in Figure 3.5, a Force Node has been added to EON simulation tree. Then the *Force Node* was specified as a prototype node for rigid bodies only. Now, the *Force Node* prototype can be applied to all the rigid bodies in the modeling environment. As illustrated in Figure 3.5, the *Force node* is simultaneously attached to the Ball and Chair objects.

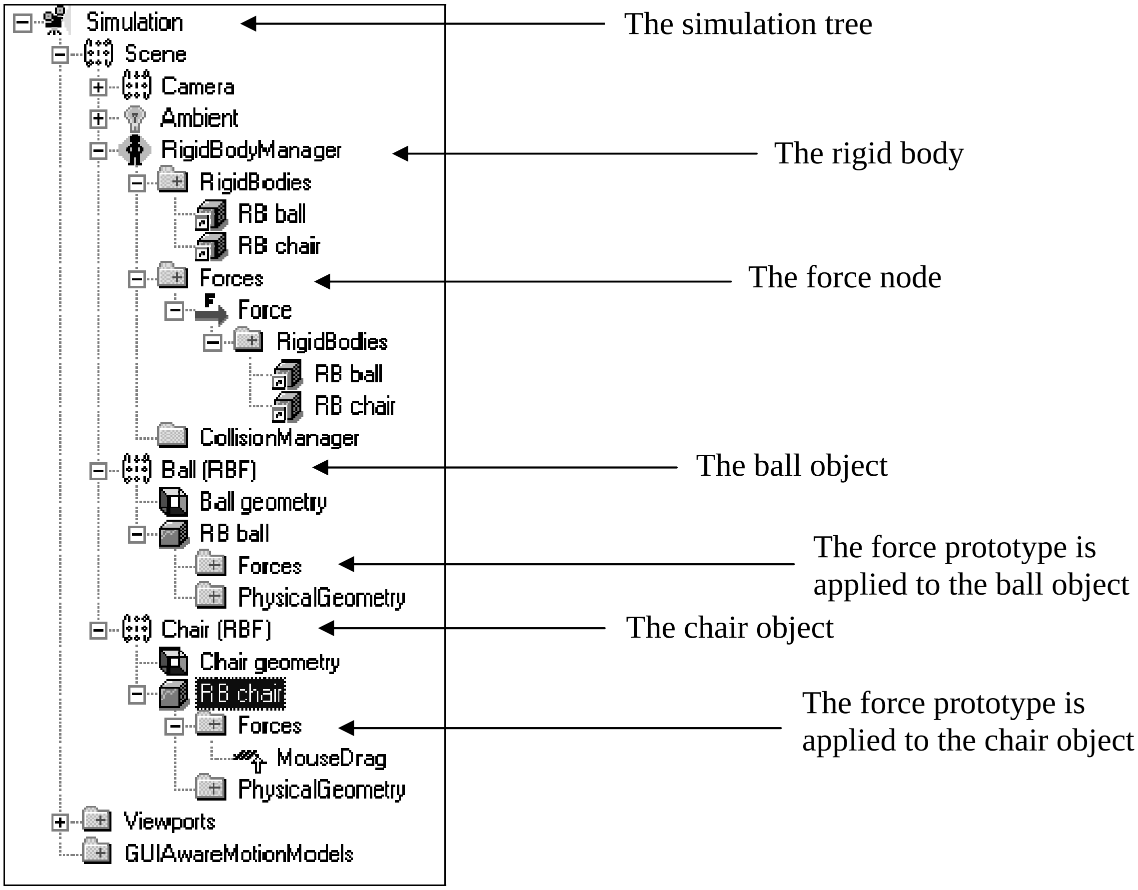


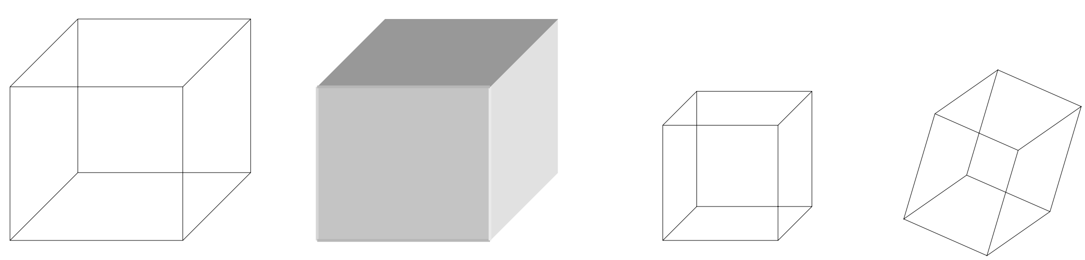
Figure 3.5: EON simulation tree: the force node prototype (EONReality, 2002).

3.10 THE USE OF PHYSICALLY-BASED MODELING WITHIN THE DEVELOPED TAXONOMY

Physically-based modeling was integrated within the developed taxonomy to create a system that models of micro/macro construction operations. The integration involves two concepts: one is the development of reusable and extensible physically-based libraries and the other involves the data exchange and the interaction process between the physically-based prototype libraries and the modeled objects.

Research in the area of physically-based modeling is moving toward the concept of prototype libraries (Brazel 1992, and Chapman, 1998). Researchers (i.e., Brazel 1992) have introduced the idea of constructing prototype libraries of computer graphics routines for physically-based modeling. The objective of the prototype library is to serve as a general, reusable, and extensible library for physically-based modeling.

Physically-based prototype libraries especially the ones that applies object-oriented technology has the potential to improve the realism of construction modeling. The prototype libraries use concepts that are similar to the ones are used in constructing objects within CAD systems. CAD systems take advantage of reusable object such as, *Box*, *Sphere*, etc. For example, in the case of using the command *Box* in a CAD environment, the user defines the length, width, height, texture, location and direction of the created Box (Box_1). As shown in Figure 3.6, Box_1 becomes a prototype and it can be reused many times as needed to create new objects with different textures, sizes, and directions. Similarly, physically-based prototype libraries can be used to prototype and define the physical behaviors of the modeled objects in the virtual environment.



Box_1 Box_1_Texture Box_1_size Box_1_Direction

Figure 3.6: A reusable object in a CAD environment.

As discussed in further details in Chapter 7.4, the interaction process will make use of the Industry Foundation Classes (IFC's) as a standard for data modeling and exchange between the 3D modeled objects and the physically-based prototypes. Physical properties prototypes libraries can then be modeled utilizing the IFC's as classes. Furthermore, recent development in three-dimensional simulation software such as EON and Deneb support the idea of physically-based modeling prototype libraries.

3.11 CONCEPTUAL PHYSICALLY-BASED MODELING OF CONSTRUCTION OPERATION – ISSUES AND CONSIDERATIONS.

Hendrickson and Rehak (1993) described a proposed example of physically-based simulation and modeling of a crane operation. The operation is to place beams in a structure using a crane that at fixed location on the site.

Table 3.1: Physically-based simulation and modeling of a crane operation (Hendrickson and Rehak, 1993).

A typical pick and place operation	
The steps of animating the operation in a state-of-art-CAD design software package	**The steps of simulating the operation in the "real" situation**
Assume the crane is initially at rest in some configuration (influenced by the self-weight and stiffness of the crane)	Assume the crane is initially at rest in some configuration (influenced by the self-weight and stiffness of the crane)
Identify the beam to be placed from those in the laydown area	Identify the beam to be placed
Swing and boom the crane over the beam	Swing and boom the crane towards the load. In the process, incorporate the mass of the crane, boom, cables, hook, etc., computing the path of the boom tip and hooks, as driven by the operator's action and the environment.
Drop the hooks to the beam	Drop the hooks to the beam (this and all other actions are influenced by the physics, etc.)
Attach the hooks to the beam	Attach the hooks to the beam

A typical pick and place operation	
The steps of animating the operation in a state-of-art-CAD design software package	**The steps of simulating the operation in the "real" situation**
Lift, swing and boom the beam into place	Lift, swing and boom the beam into place
Position the beam into the final placement position	Position the beam into the final placement position
Temporarily attach the beam to the structure Unhook the beam from the crane Move the crane for the next operation	Temporarily attach the beam to the structure Unhook the beam from the crane Move the crane for the next operation

The sequences in Table 3.1 describe a pick and move operation and compare two different scenarios of modeling and simulating the operation. The first scenario uses state-of-the-art CAD and animation software packages that enable smooth path throughout the animation process. The second scenario integrates physics with the geometrical representation of objects to simulate the operation as if it is "real."

Hendrickson and Rehak (1993) identified a number of considerations to model the operation as if it is real:

- The beam physics
- The crane physics
- The operator action
- The environment

A realistic model should also incorporate additional factors:

- Project world

- Communication
- Control
- Sensing

According to Hendrickson and Rehak (1993), “While developing and validating physical models of the type described above may be time-consuming, the basic models should be able to be re-used in numerous construction applications in the same way that standard component representations are re-used in CAD models.”

Hendrickson and Rehak have speculated on the topic of physically-based simulation in construction before computing technology was up to the task. Thus, the development of physically-based simulation in construction was complex and difficult to achieve. While, they have conceptually described an example of a typical crane motion, a pick and place operation, no further exploration was made and no applications were developed beyond the crane conceptual example. To date, computing technology is up to the task; however, there has been little substantive effort toward developing a physically-based modeling system in construction.

3.12 EXAMPLE: A CRANE LIFT OPERATION

This section reviews issues that need to be considered when modeling a construction object in line with the developed taxonomy. These issues are discussed below by looking at the individual components that constitute a crane lift operation. A crane lift operation involves the following objects and players: the object to be lifted (in this case a beam, a crane), the surrounding environment and an operator. Every object or player requires a unique physically-based modeling technique that varies in its level of complexity depending on the physical properties of each object.

The object physics. Assume that the object is a beam that is a three-dimensional object. In order to model the motion of the beam according to the law of physics, the following need to be considered: the degrees of freedom (DOF), the full 3x3 mass moment of inertia, and the kinematics constraints. The beam is a rigid object with six DOF. As shown in Figure 3.7, the first three are the translation DOF: X, Y, and Z, the others are the Rotation DOF: Pitch, Roll, and Yaw.

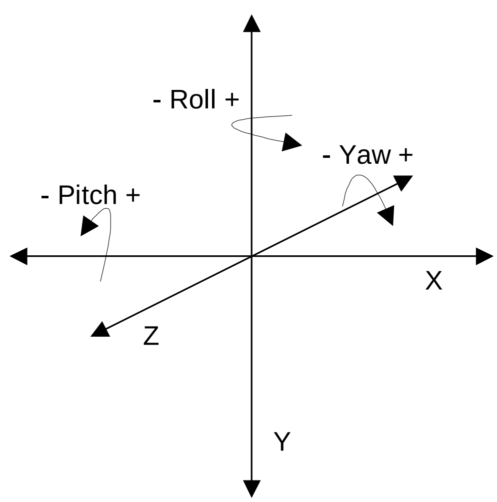


Figure 3.7: The six degrees of freedom.

The crane physics. The crane is also a three-dimensional object that consists of three major parts: the crane body, boom, and cables. Their mass and flexibility effects govern the motion of the crane. The crane control is the most critical aspect, and considered to be the most difficult to model. This is because there are many factors that govern the crane's control such as, the operator's skills, the surrounding environment (i.e., the wind, and the thermal effect), and the non-linear motion of the cable. Also, another aspect that needs to be considered is the deflection of the boom and the expansion of the cable under load.

There are two issues other than the object physics and the crane physics that are considered critical to the developed modeling taxonomy. The two issues are the surrounding environment and the operator actions. The surrounding environment adds another dimension to the complexity level of the developed modeling taxonomy. The surrounding environment such as the wind and other natural forces affects the stability of the crane under operation. Consequently, its inclusion will result in a change in the numerical model of the physical representation of the crane.

In addition to the surrounding environment the operators' actions affect the physically-based modeling of the crane in an indirect way. The operator skills have been used as a control technique during crane operations. It is an issue that affects the crane operations, however, operator actions won't affect the physically-based modeling of the crane or the load it self.

Physically-based modeling of a crane operation also involves several other issues that are not considered here of due to complexity issues. The above analysis does not intend to describe a detailed physically-based modeling of a crane operation rather than it is aimed at shedding the light on major elements that may be essential to the development of a physically-based crane model.

3.13 SYNOPSIS

This chapter presents physically-based modeling techniques and their connections to the developed taxonomy. Literature on the applications of physically-based modeling techniques were found to be limited, therefore applications from other fields, such as mechanical engineering, industrial engineering, and computer graphics are also reviewed. Additionally, this chapter establishes the advantages of applying physically-based techniques to construction modeling applications.

CHAPTER FOUR: VIRTUAL ENVIRONMENTS

4.1 INTRODUCTION

This chapter concentrates on providing an understanding of the fundamentals of virtual reality technology and the applications of virtual and 4D-CAD in construction modeling. Also, the benefits and limitations of virtual reality and 4D-CAD approaches as they relate to the developed modeling system in this research are identified. This review is important before we describe the proposed taxonomy for modeling construction operations, which will be described in chapter seven.

4.2 DEFINITIONS OF VIRTUAL REALITY

Virtual reality (VR), virtual environment (VE), virtual world or microworld are equivalent names that refer to the same concept. Many definitions for VR can be found in the literature due to the interdisciplinary nature of the field. Nevertheless, the different definitions agree on some basic elements of VR. Namely, a VR system is a combination of a human participant, human-machine interfaces, and a computer with the objective of immersing the VR participant in an interactive environment, which contain 3D objects with 3D locations, and orientations in 3D space.

The CAVE (Automatic Virtual Environment) is a projection-based VR system that surrounds the user with four screens. The screens are arranged in a cube made up of three rear-projection screens for walls and a down-projection screen for the floor. A user wears stereo shutter glasses and a six-degrees-of-freedom head-tracking device. As the user moves inside the CAVE, the correct stereoscopic perspective projections are calculated for each wall. A second sensor and buttons in a wand held by the user provide interaction with the VE.

VR can be defined as follows (Gigante, 1994):

"The illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on 3D stereoscopic head-tracked displays, hand/body tracking, and binaural sound. VR is an immersive, multi-sensory experience."

VR can also be defined as follows (Furness and Barfield, 1995):

"The representation of a computer model or database which can be interactively experienced and manipulated by the VE participant(s)."

The difference between a VR system and conventional computer graphics is that, in the latter, the user is like an external observer looking through a window while in the former, the user is a participant in the synthetic environment. Other concepts related to VR are the following:

- Virtual image (Furness and Barfield, 1995): the visual, auditory, tactile and kinesthetic stimuli, which are conveyed to the sensory such that they appear to originate from within the 3D space surrounding VR participant.
- Virtual interface (Furness and Barfield, 1995): a system of transducers, signal processors, computer hardware and software that creates an interactive medium.
- Augmented reality (Durlach and Mavor, 1994): "the use of transparent head-mounted displays that superimpose synthetic elements on a view of real surrounding."
- Artificial reality (Gigante, 1994): video-based, computer mediated interactive media.
- Cyberspace (Gigante, 1994): a global information and entertainment network.

4.3 HISTORY OF VIRTUAL REALITY

VR is often thought as a new technology, but its development actually dates back almost 40 years ago. In 1962, Heilig (Gigante, 1994) presented the Sensorama, which was the first multi-sensural simulator where the viewer could take a motorcycle ride through New York City. The simulator constituted a VR system with the lack of interactivity. In the middle 60's, Sutherland (Ellis, 1995) developed fast graphics hardware for the purpose of experiencing computer-synthesized environments through head mounted displays. In the 70's, Krueger (Ellis, 1995) implemented an interactive environment that was projected onto a wall-sized screen. Krueger's environment is an early version of what we know now as the Cave Automated Virtual Environment (CAVE), developed by the University of Illinois.

In the 80's, great advances were achieved in the area of vehicle-simulators, especially military flight simulator (Gigante, 1994). Since teaching some of the flight skills on real vehicles were dangerous and/or expensive, it was important to develop flight simulators for training and testing of new technology and procedures. In the middle 1980's, the Virtual Interactive Environment workshop (VIEW) developed a general-purpose, multi-sensory, personal simulator device (Ellis, 1995). There are numerous other applications and contributions in the field of VR from different research groups and entertainment industries that can be found in the literature.

4.4 USING VR AS A DESIGN TOOL

At the LEGO group, maker of the world's most popular toys, engineers and designers are working in collaborative and immersive simulation based environment. The LEGO group has been engaged in CAD engineering for many years. The company uses a 3D graphics database of toy kit elements to develop future toys. The design team uses the database with Multigen's immersive 3D-scene assembly package, SmartScene, to create the LEGO virtual village (LEGO, 1998). The designer enters the LEGO village by putting headmount displays and pinch gloves that are equipped with a tracker system. Inside the VE, the designer accesses hundreds of photorealistic LEGO parts. They appear in mid-air, ready to grab by hand for building. After the scene is complete, the system generates a parts list and a physical model is then generated. If it looks promising in physical reality, then it is ready to be manufactured. This case of the LEGO group demonstrates the use of a non-sequential design process within a VE.

4.5 USING VR TO IMPROVE DESIGN PROCESSES

Chrysler uses VR technology to improve both interior and exterior aesthetic evaluations in the early stages of the design (product) development. According to Ken Socks

(Chrysler, 1998), an engineer at Chrysler, “to accurately evaluate and modify designs, you need accurate representations of them in a VE. Our models are really more accurate than a physical prototype because they’re based on all of the actual CAD models.” Therefore, the use of VR in the design process may improve the design quality, enhances product safety, and reduces cost. Additionally, with the ability to see, walk, reach, and grasp in the virtual world, manufacturers can train personnel and greatly improve worker’s safety and productivity.

4.6 AUGMENTED REALITY IN CONSTRUCTION

Augmented reality is poised as a new technology ready to tackle many real world applications. Augmented reality is generally defined as enhancing the real world with computer-generated information to improve understanding. There are many applications that can take advantage of augmented reality systems: entertainment, manufacturing, assembly, product design, medical training, collaborative work, scientific visualization, architecture design, construction, and any area that can be reasonably enhanced.

Augmented reality has been used at the Columbia University by Anthony et al. (1996) to develop systems that improve the methods for the construction, inspection, and renovation of architectural structures. Webster et al. (1996) demonstrated an experimental augmented reality system that shows the locations of columns behind a finished wall, to determine the locations of re-bars inside one of the columns, and to conduct structural analysis of the column (Webster et al., 1996).

4.7 VIRTUAL ENVIRONMENTS IN ARCHITECTURE

VE is a system that creates an artificial three-dimensional world where communication is interactive with an immediate response. Also, it is a real-time simulation technology where the viewer is able to move about the 3D model.

VE create a powerful sense of immersion inside a 3D graphical computer model. Participants are immersed and surrounded by information, which is to scale and three-dimensional. The Cave Automatic Virtual Environment (CAVE) interface is intuitive to use for exploring VE because it is tightly coupled with the way people explore real environments. Viewers can look around in the 3D building model by turning and moving their heads, as they do naturally in a real space.

VE systems combine a head mounted stereo display device with data gloves, data suits, and similar devices that interpret bodily movement. VE systems allow the user to "pick up" full scale three-dimensional geometrical entities and "carry" them to where the user wants to locate them in space (Licklider et al., 1978).

4.8 VR MODELING TECHNIQUES IN ARCHITECTURE

VR have the potential to be excellent representation tools for helping designers make decisions about architectural spaces before they are built. Engeli and Kurmann (1996) introduced a new method of modeling 3D architecture spaces to support design development in the early stage using VR. As a demonstration of their idea they developed SCULPTOR, which is a computer tool for virtual design in architecture. SCULPTOR adopted the idea of modeling void architectural spaces as its main modeling technique.

Designing with void spaces is a major design method architects use to design conceptual spaces within a building during the schematic design phase. SCULPTOR uses two types of volumes as shown in Figure 4.1 positive (solid) and negative (void). (Engeli and Kurmann, 1996).

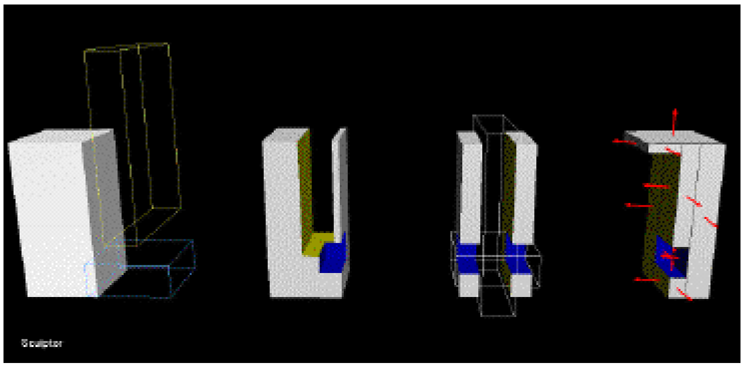


Figure 4.1: Positive and negative volumes (Engeli and Kurmann, 1996).

Furthermore, Cost Agent, a separate program that communicates with SCULPTOR, and estimates the cost of the project based on the kind and size of the different rooms that compose the project volume (Engeli and Kurmann, 1996). Cost Agent is an adequate tool for designers at the schematic design stage.

At the early stages of the design process, designers tend to describe their designs as void and negative spaces and relationships within the spaces, while construction managers and contractors visualize it as components and sub-components and ways to assemble them. Accordingly, SCULPTOR because of its modeling technique, which uses void and negative volumes, is an ideal environment for designer. However, SCULPTOR lacks the ability to explain construction methods, productivity, quality, and safety.

4.9 PROTOTYPING TECHNIQUES USING CAD AND VR

Prototyping is a technique to generate designs quickly in both conventional CAD and computer graphics systems. Conventional CAD systems use the "library" approach that provides a choice of elements, which can be copied into the new design (Coomans and Oxman, 1996). These elements could be statically defined such as furniture and engineering symbols, or could be parametric such as doors and windows. "Menu" is another common approach in computer graphics systems, which provides a menu of elements and also a range of possible procedural operations upon these elements (Coomans and Oxman, 1996). The second approach is more appropriate for modeling construction operations because of the ability to add intelligence to the element behaviors with respect to the corresponding construction operation. Intelligence means that the elements or the components involved in any construction operation will behave to a certain degree within the VR as it would in the "real" world. The physical behavior of the element within the VR could be one form of intelligence. For example, objects fall down when released in the air.

Coomans and Oxman (1996) developed their prototype system called VIDE, the acronym for Virtual Interactive Design Environment. The main purpose of developing VIDE is to investigate the technical practicability of a VR based design system. The VIDE design system capabilities were devoted and limited to the room design task. The system allows the users to define the room design components such as apace boundaries, boundary penetrations, and furnishing. It also restricts the operations that can be performed on those components to adding, removing, and relocating. The idea of breaking down a project into its component, material or design space components, and defining tasks that are linked to these components could be perfectly implemented in a construction operation modeling system.

4.10 VIRTUAL REALITY IN CONSTRUCTION

4.10.1 USING VR FOR TRAINING IN CONSTRUCTION

The use of computer simulation as a training tool for construction personnel can eliminate expensive errors from happening during actual construction. Recent advances in computer technology, both real-time computer graphics and hardware, made it possible for a new cost effective method of training construction personnel (Wakefield et al., 1996). At the University of New South Wales (UNSW) and the Tasmanian Building and Construction Industry Training board, Wakefield et al. (1996) developed an interactive excavator simulator for operator training. As a demonstration of the effectiveness of the simulator, they created a hydraulic excavator simulator prototype suitable for training novice operators and test it in service (Wakefield et al., 1996).

According to Wakefield et al. (1996) and as demonstrated in Figure 4.2, “The operator controls, the computational model, the graphics system, and the system are together using the system interfaces to form the functional excavator simulator.” The computational model is the mathematical model that performs all the calculations related to the state of the simulated system. The graphics system produces 3-D graphics images prospectively accurate and updated in real time, based on the information generated by the computational model. The system interfaces enable the integration of the operator controls, the computational model, and the graphics system to structure the combined simulator (Wakefield et al., 1996). Cost, time, the ability to train on different machines, and performance recording are advantages of the simulator over traditional training on the conventional excavator.

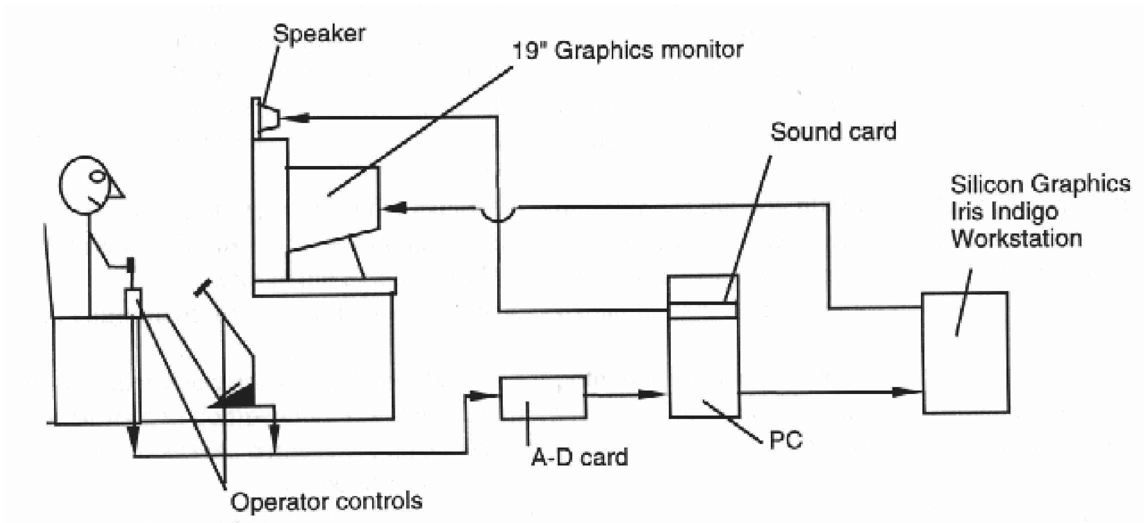


Figure 4.2: Excavator simulator layout (Wakefield et al., 1996).

Barsoum et al. (1996) and Soedarmono et al. (1996) developed an interactive training tool, SAVR, to model safety in construction using VR technology. Barsoum et al. (1996 said: “The objective of SAVR is to develop a tool for construction workers to perform ‘on the job’ safety training and to promote an accelerated learning experience in hazardous working conditions without actually being there.” The development of the environment consists of two major phases. First, the creation of three-dimensional objects using 3D Studio, which is a modeling and animation software from Autodesk, and World Tool Kit (WTK) graphical user interface, WTK is a simulation package from “Sense 8”. Second the development of the VE using WTK graphical user interface. Barsoum et al. (1996) give detailed description of the development process of the SAVR environment as shown in Figure 4.3.

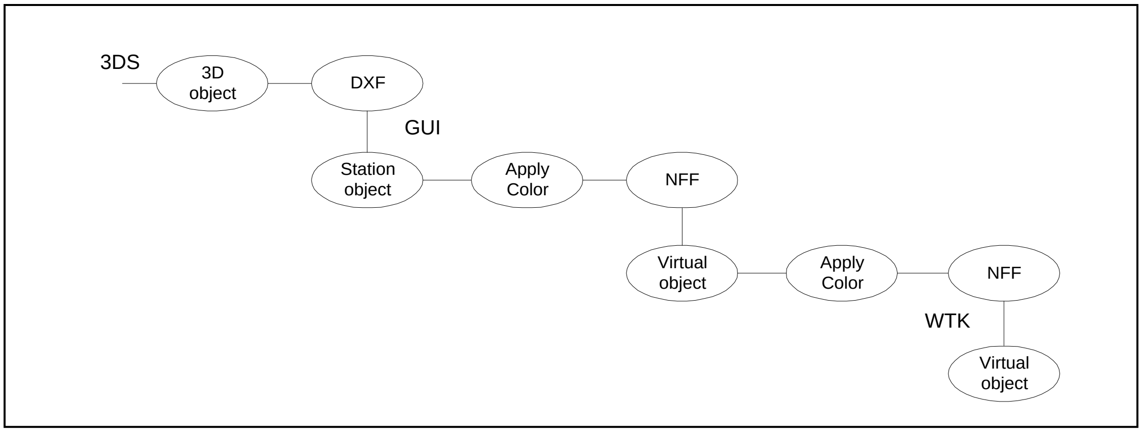


Figure 4.3: The process of creating a virtual world (adopted from Barsoum et al., 1996).

4.10.2 VR AND CONSTRUCTION ROBOT PROGRAMMING

Navon and Retik (1997) presented a new approach of robot programming with the aid of VR. The use of VR allowed them to learn more about the geometry and spatial arrangements of a given design, explore the best way to perform a task using human reasoning, and train the robot for designated tasks in the same way workers have been trained to perform new tasks.

4.10.3 USING VR TO SIMULATE EQUIPMENT-BASED CONSTRUCTION OPERATIONS

In the area of using VR to simulate equipment-based construction operations, Opdenbosch (1994) developed a VE specially designed to simulate such operations in a real-time virtual interactive environment. The VE was developed using an object-oriented C++ language, called Interactive Visualizer Plus Plus (IV++). Within IV++, construction planners choose different virtual equipment to perform construction operations. IV++ was originally driven from a multipurpose VE, the interactive visualizer (IV).

Opdenbosch (1994) also developed a new technique, Computer Aided Design and Assembly (CADA), to simplify the process of defining assembly simulation goals by using CAD. The goals are contained in the building model (BO), which is created using CADA. BO is a building object definition file that contains the assembly sequences and machine instructions to be rendered in the VE. The interface between the building model components and the virtual equipment is called the planner. The planner takes care of generating the sequence of instructions, using the available resources, to complete an assembly goal. The sequences are determined by the order in which building components are scheduled to appear in the environment.

There are three types of data associated with CADA:

1. The geometric information associated with the building primitives. A standard building primitives data file includes the geometry, action, material, initial location, initial orientation, coordinates, and color.
2. The hierarchical information that establishes the relationship between the building components. The hierarchy is determined by the dependency that exists between components. An example is shown in Figure 4.4.
3. Priority information, which is used to ensure that preconditions of a procedure are fulfilled.

The methodology of simulating the construction of a building consists of the following five steps (Opdenbosch, 1994):

- Design the building using CADA.
- Run the simulation with all the relevant elements such as cameras and lights.

- Choose the virtual equipment.
- Start the assembly process.
- Turn to the VR.

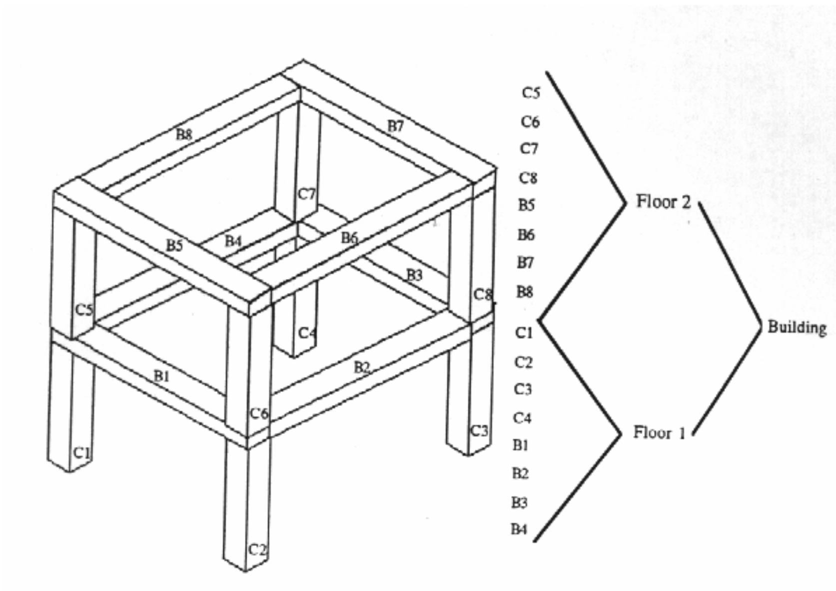


Figure 4.4 Hierarchical distribution of building components.

Similarly, at the University of Florida, Naji (1997) developed a VE called SIMCON (SIMulating CONstruction operations) to simulate equipment-based construction operations with real-time user interactions. CAD development software was used to develop the 3-D models of the environment (i.e. building components and equipment). Object-oriented modeling techniques were also used to describe the hierarchical relationships between objects. The 3-D CAD objects were assembled in the SIMCON environment and the graphical user interface (GUI) was developed using a scripting language (BASIC Script).

OpdenBosch (1994) and Naji (1997) introduced new ways of modeling equipment-based construction operations using 3-D graphical output representations in real-time VE. In their work, they focused on modeling the equipment-based construction operations in specific and the building components and site in general. IV++ and SIMCON are valuable examples of how a VE can be employed for construction simulation using supercomputers and personal computers. However, a more in-depth study is needed in the areas of physically-based modeling techniques, task-oriented modeling techniques, and modeling of building components during construction (Hendrickson and Rehak, 1993, Everett, 1991, AbouRizk et al., 1992).

4.10.4 VIRTUAL REALITY MODELING IN CONSTRUCTION

Tsay et al. (1996) developed a VR model of a bridge construction. The model allows the construction engineers to interact virtually within the model using input devices to move objects, connect and erect steel girders, and cast concrete for the bridge deck. The development process of the environment consisted of three phases:

1. 3D-object modeling, AutoCAD and 3D Studio was used to create the 3D objects.
2. Programming an interactive construction site, the C language library from “Sense 8” was used to develop the virtual model.
3. Incorporating tracking devices into the system.

This system can be categorized as a tool to train construction engineers to adequately construct a bridge superstructure.

4.10.5 VIRTUAL CONSTRUCTION SITE

Hendrickson and Rehak (1993) speculated the idea of using a computer-based “virtual construction site” (VCS) model to investigate alternative designs for sensing, site modeling, distribution processing, and automation on construction sites. Also, they discussed the importance of implementing physically-based modeling to achieve realistic representation and assessment of automation and process design alternatives.

The benefits of developing a VCS model as Hendrickson and Rehak (1993) point out are:

- VCS models would represent an example of the next generation of CAD systems in which engineering information could be accurately simulated.
- VCS models could be adopted for site logistics planning, in which the planner could “move” equipment and the feedback would reflect cost and time implications of the selections.
- VCS models might be useful in the design and selection of hazardous site remediation strategies.

4.11 4D-CAD MODELING IN DESIGN AND CONSTRUCTION

4.11.1 INTRODUCTION

4D models integrate 3D CAD models with construction activities to display step-by-step sequence of construction over time. This integration is accomplished through a third-party knowledge-based system capable of integrating graphical and non-graphical information. One of the earliest systems to use CAD technology for the purpose of planning, scheduling, and controlling the construction process was developed by Bechtel

Western Power Co. and Bechtel Construction Inc. (Morad, 1990). This system combines intelligent 3D CAD models, state of the art computer graphics capabilities, knowledge-based decision support features, and a CPM schedule processor to display the progression of construction over time.

Similarly, Stone and Webster Engineering Corp. (Morad 1990) developed a computerized database system to integrate graphics, engineering data, and all other information necessary for the engineering, design, construction, operation, and management of facility.

Later, research has been carried out to integrate 4D with product model tools to improve the quality of interdisciplinary collaboration. The product model and fourth dimension (PM4D) approach represents such efforts (Fischer et al., 2002, VTT, 2003). For instance, it has been used during the design and construction of the HUT-600 in Finland. The PM4D approach was used to construct and maintain object-oriented product models of building components, spatial definitions, material composition, and other parametric properties. The product models used in this approach are based on open industry foundation classes (IFC), which improved data and information exchange between the project participants and their tools.

4.11.2 RESEARCH AT VIRGINIA TECH

Research at Virginia Tech was done to develop a CAD-based construction system (Skolnick, 1990). The outcome of this research is the KNOW-PLAN and VSS systems. KNOW-PLAN is a knowledge-based system that integrates artificial intelligence technology with computer aided design technology to generate and simulate the construction schedule of activities (Morad and Beliveau, 1990). The KNOW-PLAN system generates a schedule of construction activities based on knowledge extracted from 3D computer models as well as other knowledge sources. The system visually simulates the construction based on the generated sequence of activities. It allows the user to view the step-by-step sequence of construction using the 3D computer model of the designed facility.

VSS is a visual schedule simulation system developed at Virginia Tech. VSS is a system that integrates traditional computer-based scheduling techniques with 3D CAD computer modeling to provide a visual simulation of the construction sequence (Skolnick, 1990 and Skolnick et al., 1990). The VSS system consists of three primary phases. Phase I is the date preprocessor, which consists of preparing the CPM schedule (Primavera Project Planner) and 3D computer model (CADAM) for a construction project. Phase II is the database manager (dBASE IV), which maps the activities in the CPM schedule to each object in the 3D computer model. Phase III is the visual simulator, which uses a computer-based 3D simulation and visualization system (WALKTHRU).

4.11.3 RESEARCH AT BECHTEL CORPORATION

Bechtel Corporation has developed a planning graphical simulation tool called 4D-Planner (4DP) that allows project managers and construction planners to create interactive project simulations (Williams, 1996). The purpose of 4DP is to link the 3D CAD model components to the associated network schedule activities. Williams (1996) gives a detailed description of the 4DP and how it can be used as a visualization, simulation, and communication tool.

The features of 4DP are the following:

- Provides simultaneous access to design and scheduling data.
- Provides a graphical simulation of the work plan.
- Allows early problem detection, including interference.
- Supports scenario analysis and “what-if” planning.
- Facilitates inter disciplinary constructability reviews.
- Helps optimize work plans and schedules.
- Provides a means to graphically represent the results for the planning process.

4.11.4 RESEARCH AT STANFORD UNIVERSITY

4D-CAD models (3D CAD plus time) are becoming more common in design and construction (Fischer et al., 2002). 4D CAD models are currently being used as a planning, communication and visualization tool. It allows the project participants to simulate and visualize the sequence of the construction operations in time. Currently the product model and fourth dimension (PM4D) research efforts have been carried out to link product models with 4D-CAD models (Fischer et al., 2002). Such efforts have been translated and tested during the design and construction of Helsinki University of Technology Auditorium Hall 600 (HUT-600) project in Finland.

According to Fischer et al. (1996), “Conceptually 4D-CAD is a medium representing time and space, a type of graphic simulation of a process. In construction, a 4D animation simulates the process of transforming space over time and reflects the four-dimensional nature of engineering and construction.”

In comparison to Bechtel's 4DP, the fundamental purpose of 4D CAD models is to produce 4D simulation by relating the 3D graphical model components (e.g. 3D CAD models) with the construction network schedule activities (e.g. a schedule produced with Primavera Planner). This can be achieved by importing the CAD model components and the schedule into a third party simulation environment (e.g. PlantSpace). PlantSpace is a suite of application products, which collectively function as a data integration application (Jacobus Technology, 1997). Within the simulation environment, relationships between the CAD model components and the schedule activities are created.

4.11.5 4D APPROACHES

As discussed earlier, 4D models integrate the 3D geometrical representation of the building components with their corresponding scheduling data. The integration process has resulted in the improvement of 4D modeling concepts and implementations. There are several approaches for integration (VTT, 2003); however the two most developed and promising approaches are the automation approach and the linking approach.

The automation approach refers to the generation of 4D models where a reasoning engine or engines together with construction operations knowledge are able to interpret 3D geometric data and produce visual simulation showing how the designed facility can be constructed.

There are two categories of 4D CAD that fall under the automation approach: The first category is visual 4D CAD and the second is collaborative 4D CAD. Visual 4D-CAD succeeds in creating 4D animation by linking the construction schedule to the 3D-CAD model components. Fischer et al. (1996) described the processes and the software technology involved in producing a visual 4D CAD for the San Mateo County Health Center (see Figure 4.5). Visual 4D CAD is a powerful tool; however, it has some limitations such as:

1. *Time and effort consumption:* The initial need for a complete 3D model created from 2D drawings requires large investment of time and effort.
2. *Interactivity*: The CAD model components and schedule activities are created in different applications, which prevents the user from interactivity and knowledge gained during the process of composing the schedule.
3. *Process updating:* Any changes in the CAD model or schedule require that the user re-link all activities to their corresponding CAD elements.
4. *No true process information:* A true process system defines and captures a set of partially ordered steps in which applied resources transform material and equipment resources into constructed product.

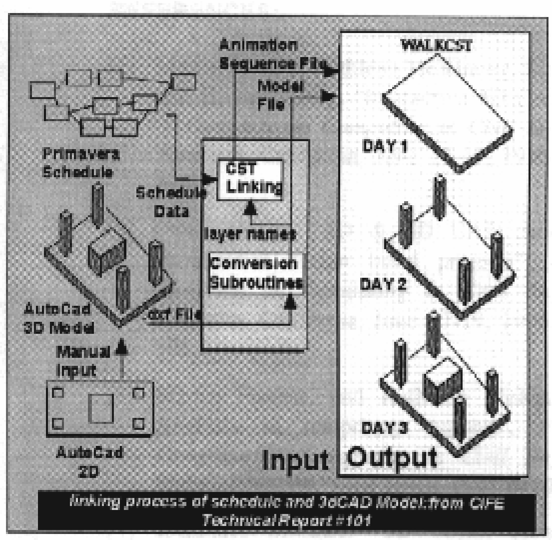


Figure 4.5: 4D-Modeling process for visual 4D CAD (Fisher et al., 1996).

Collaborative 4D CAD improves upon the limitations of visual 4D CAD. It produces 4D animations of the 3D CAD components corresponding to their schedules, which enable the designers to collaboratively evaluate their designs and schedules. Visual 4D CAD illustrates the effectiveness of visual simulation. On the other hand, collaborative 4D CAD focuses on the interactive and collaborative design of the construction process, including the schedule requirement that may constrain the process. Whereas visual 4D CAD merely reflects the process of creating relationships between time and space, collaborative 4D CAD consists of product and process information (Fischer et al., 1996).

The second and present approach is the linking approach. The linking approach links 3D building model with project task model. Where the 3D building model data encompass the geometry of the constructed facility the task model include task scheduling details. The project task model refers to task data extracted from a scheduling engine. In this approach the 3D building model data uses the IFC to provide the standard for storing all required information.

There are five basic steps to produce a 4D Model using the linking approach (VTT, 2003). The first step is to generate a 3D geometry of the designed product in IFC format. This can be achieved by designing the product in 3D utilizing a CAD system with an IFC compliant object-oriented platform. The second step is to create activity driven schedule of the product with a CPM scheduling engine (for instance, MS Project). The third step is to link the 3D objects defined in the IFC model with the corresponding tasks defined in the task model generated from the scheduling engine. The linking process enables the IFC model of 3D object to capture timing information from the task model.

As shown in Figure 4.6, the linking can be accomplished by utilizing the ‘4D Linker’ tool provided by VTT and Eurostep (VTT, 2003). The 4D Linker is a tool for browsing the building product model data together with the task model data. It allows the user to select a single or multiple product components and create a link between the task and those components.

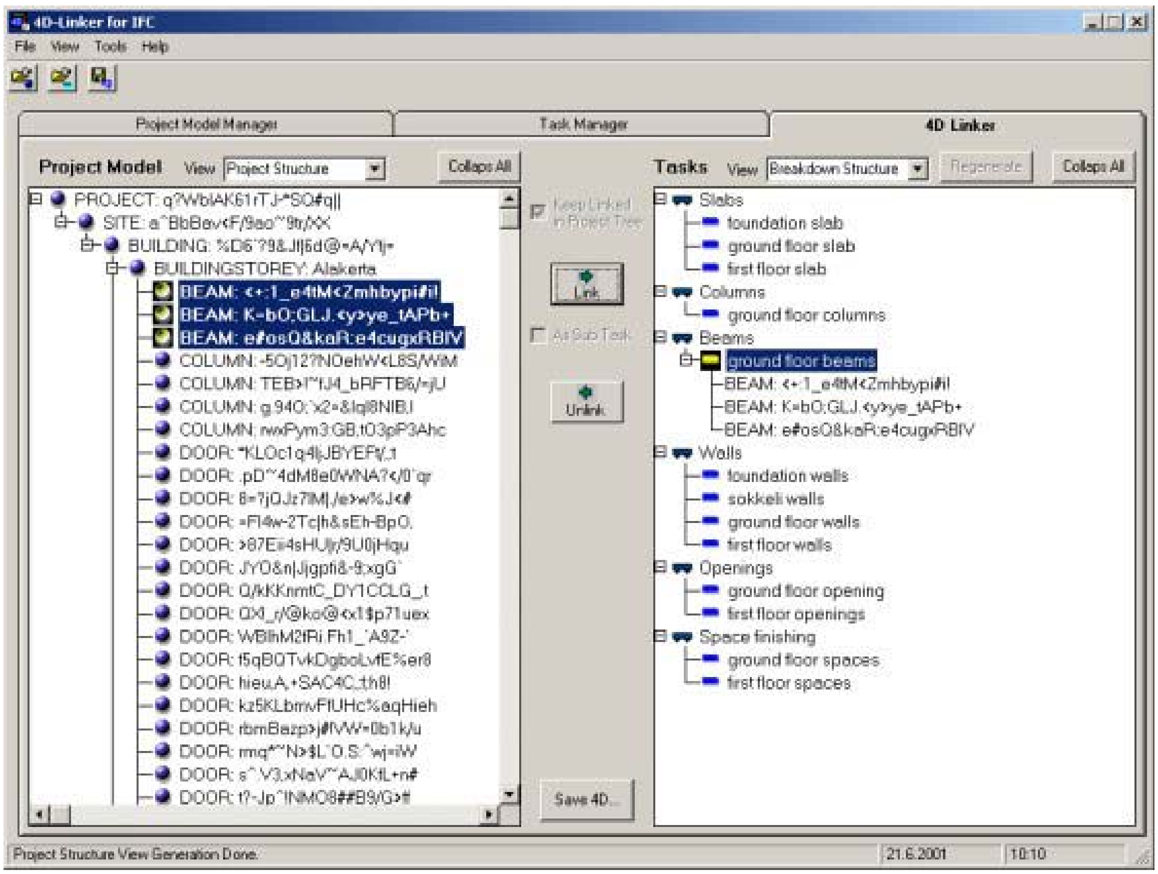


Figure 4.6: Screen shot of 4D Linker interface (VTT, 2003).

The last two steps involve the creation and simulation of the Virtual Reality Modeling Language (VRML). The VRML model of the IFC objects is created using a 4D converter. As shown in Figure 4.7, the VRML model can be viewed using the WebSTEP tool through a standard web browser. Furthermore, at anytime changes can be made to the 3D model and schedule. Any changes to the model can be updated semi-automatically using 4D Linker.

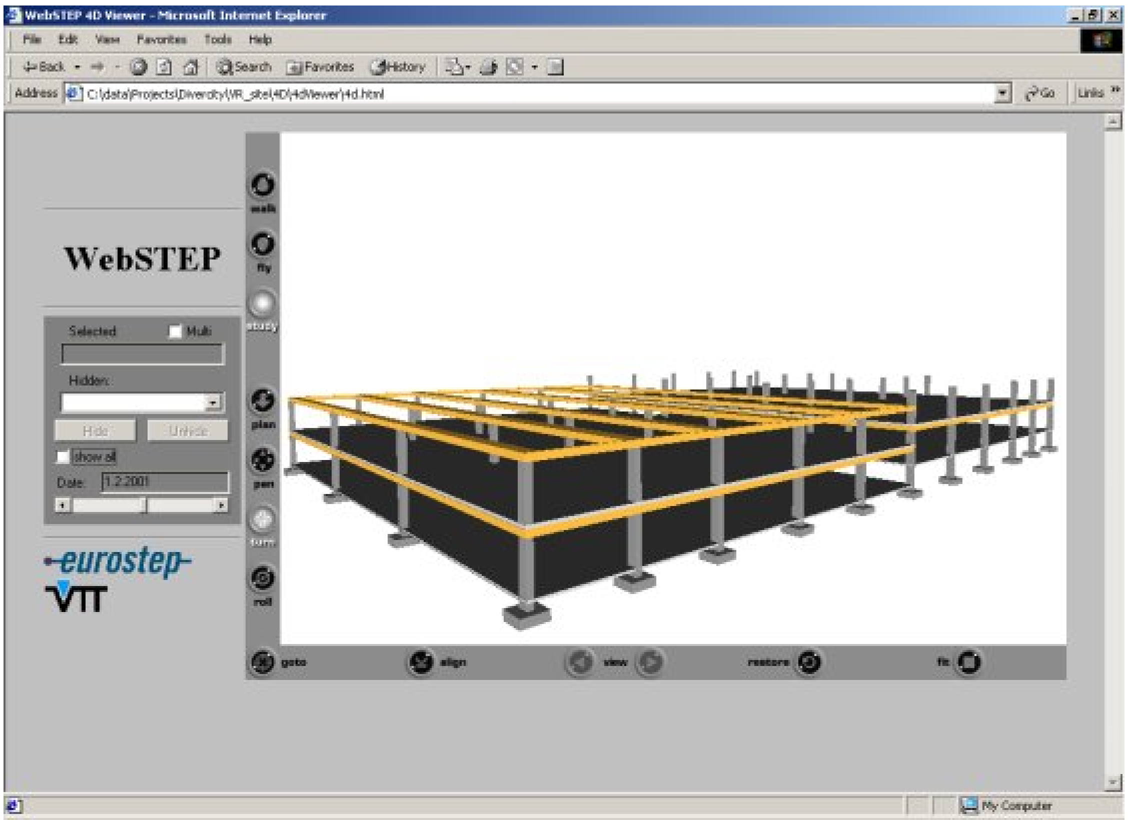


Figure 4.7: Screen shot of WebSTEP 4D viewer (VTT, 2003).

The VTT project shows the potential use of 4D modeling to simulate construction processes and improve project delivery. It also shows the available techniques and technologies that are used in 4D model generation (Fischer and Kam, 2002, VTT, 2003).

Nonetheless, the 4D linking approach is similar to the PlantSpace integration techniques developed by Jacobus Technology. Both approaches provide similar environments that enable data integration between applications. However, the abilities of both approaches are limited to visualization and fall short in providing a system where processes can be modeled. In other words, the 4D visual modeling approaches don't contain true process information. The ability to model construction processes and capture the information associated with them are essential to analyze and improve construction operations.

4.12 SYNOPSIS

Chapter Four reviews the fundamentals of virtual environments and the application of virtual and 4D-CAD modeling approaches in construction. The advantages and limitations of these approaches in relation to the developed modeling system in this research are identified. Virtual environments are identified as excellent representation medium for visualizing construction operations. Nonetheless, in addition to existing virtual modeling environments and 4D-CAD approaches, a new improved modeling system that has the ability to model, record and analyze construction operations is needed.

CHAPTER FIVE: CONSTRUCTION AUTOMATION AND ROBOTICS TECHNOLOGIES

5.1 INTRODUCTION

This chapter reviews research conducted in the area of automated and robotic technologies specifically developed for the construction industry. Also, this chapter analyzes the distribution of work between humans, tools and equipment based on their physical and information contributions. In the past decade, research and development of construction automation and robotics has advanced rapidly to the point where many technologies are close or in commercial use (Skibniewski et al., 1986, Navon, 1995, and Slaughter, 1997).

Robots are used in construction operations; to improve safety of workers and eliminate dangerous operations; to increase productivity; and to improve final quality (Kangari, 1988, Slaughter, 1997). Additionally, opportunities for construction automation can be improved by analyzing human, equipment and construction operations to determine how they interact among each other.

5.2 DEFINITION

A widely accepted definition by Robotics Industry Association characterizes robot as reprogrammable multifunctional manipulator designed to move material, parts, tools, and specialized devices through variable programmed motions for the performance of a variety of tasks (Slaughter, 1997). Nevertheless, this definition is inadequate for construction robots. Whittaker and Bandari (1986) simply characterize construction robots as “robots that can constructs, meaning builds, and yet such robots do a lot more; they exhibit flexibility in the roles they play and the equipment they use, and they perform tasks of a complexity that previously required human control.” Furthermore, automation is a combination of man and machine, while robotization is machine only (Everett, 1991).

5.3 TYPES OF ROBOTS

In general, robots can be classified into three categories: teleoperated robots, programmed robots, and cognitive robots. Each distinguished by the control procedures available to the robot and its relationship to human supervisors (Whittaker and Bandari, 1986). Teleoperated robots, includes machines where humans control all planning, perception, and manipulation. Further, teleoperation is evolving robot forms and bodies suited to unstructured tasks and environments. Programmed robots, in this category robot perform predictable, invariant tasks according to pre-programmed instructions. While programmed robots are the backbone of manufacturing, it has limited use in construction. This is because this type of robots is suitable for predictable and invariant tasks, whereas construction robot must be able to recognize and responds to unknowns and unplanned difficulties. Cognitive robots can sense, model, plan and act to achieve goals in the manner of teleoperators but without human supervisors (Whittaker and Bandari, 1986).

5.4 POTENTIAL USE OF ROBOTICS IN CONSTRUCTION

Everett (1991) proposes that the best opportunities for construction automation occur at the basic task level. The basic tasks are: connect, cover, dig, finish, inspect, measure, place, position, spray, and spread. An earlier statistical study by Kangari and Halpin (1989) justifies that basic tasks are more suitable for automation than activities.

Kangari and Halpin (1989) examine the potential use of robotics in construction. Their study analyzes thirty-three construction processes based on three major criteria and several sub-criteria for each of them. Three major criteria are identified: need based feasibility, technical feasibility, and economic feasibility. Need consists of ten sub-criteria: labor intensiveness, vanishing skills, requires high skills, dexterity and precision, repetitiveness, tedious and boring, critical to productivity hazards, and physically hazardous. Five sub-criteria of technology are identified: material handling requires sensors, control software, control hardware, and end effector. Economics include three sub-criteria: productivity improvement, quality improvement, and saving in labor.

For each construction process, a normalized rating on a scale of one to ten was assigned for each sub-criterion of the three major criteria, with ten indicating the highest feasibility for robotization. Normalized weighted average was then calculated for each criterion. Kangari and Halpin's thirty-three construction processes and the corresponding normalized weighted averages for the three major criteria are shown in Table 5.1. For example, the normalized weighted average for activity formwork is 4.3, while it is 8.7 for basic task wall finishing. In other words, the basic task wall finishing is better suite for automation than activity formwork.

Table 5.1: Robotization feasibility (Kangari and Halpin, 1989).

	Need	**Technology**	**Economics**	**Weighted Average**
Bush hammering	8.7	6.1	5.3	6.7
Concrete placement	7.4	7.4	9.1	8.0
Crane operation	2.7	7.1	5.1	5.0
Decking	3.1	3.2	5.1	3.8
Ditching	4.7	9.2	7.1	7.0
Drywall	7.4	6.3	7.5	7.1
Ductwork	1.7	3.2	6.4	3.8
Fireproof/spray	7.0	8.8	8.2	8.0
Formwork	4.9	1.3	6.7	4.3
Grading	4.3	9.2	3.0	5.5
Insulation/siding	4.8	6.5	8.7	6.7
Layout/survey	3.2	9.2	1.2	4.5
Masonry	6.8	7.2	7.3	7.1
Painting	9.2	9.2	9.1	9.2
Pile driving	7.2	4.3	4.6	5.4
Piping/plumbing	1.0	1.1	8.4	3.5
Piping/underground	5.1	5.7	8.7	6.5
Post-tensioning	3.1	8.2	3.9	5.1
Precast/cladding	5.6	6.7	6.4	6.2
Precast/structural	5.0	4.2	6.4	5.2
Rebar placement	6.0	7.6	8.7	7.4
Sandblasting	9.2	8.9	8.4	8.8

	Need	Technology	Economics	Weighted
Scaffolding	4.1	1.1	4.8	3.3
Slurry walls	4.1	6.8	6.4	5.8
Sprinkler piping	3.0	4.2	8.0	5.1
Steel fabrication	6.4	9.3	8.7	8.1
Steel structural	4.7	5.4	8.7	6.3
Tiling	7.4	6.7	9.1	7.7
Tunneling/cast	8.7	7.1	6.6	7.5
Tunneling/cut-muck	9.7	9.9	6.6	8.7
Tunneling/hand	9.5	9.9	6.6	8.7
Tunneling/precast	7.6	9.9	6.0	7.8
Wall finishing	8.4	9.2	8.7	8.8

5.5 THE DEVELOPMENT OF CONSTRUCTION ROBOTS

Navon (1995) has identified three development processes of construction robots as follows:

1. Evolutionary type, this development process type involves increasing the level of automation by providing the conventional construction equipment with computing, control, and sensing capacities.
2. Revolutionary type involves adapting of construction technologies and robots of this type are specifically designed to perform construction operations. SHAMIR is considered to be an example of this approach.
3. Intermediate one, whereby prototypes of construction robots are assembled from off-the shelf component. The drawback of the approach is that it requires very large budget.

Navon (1995) describes a methodology used for the development of the Surface Horizontal Autonomous Multipurpose Interior Robot (SHAMIR). SHAMIR is designed to perform the major activities. First, horizontal surface treatment such as, grinding concrete, cleaning floors with a vacuum, and finishing concrete floors. Second, floor covering such as, tile setting, covering floors with carpet, and coating floors with liquid materials. Third, sealing joints between prefabricated slabs or between tiles. Finally, general assignments for example, quality control task and service tasks.

Navon's methodology is divided into five stages: performance specifications, conceptual design, computer-graphic-based testing, detailed design, and construction of a prototype. Navon's introduced and integrated the graphic-simulation-based process to the traditional development practices of construction robots. The graphic simulation stage permits the analysis of parameters as early as the conceptual design stage. This analysis is normally associated with the detailed stage. The five stages of Navon's methodology are as follow:

1. Performance specification, which refer to the activities to be performed by the robot, the material supply system for each activity, the method of execution, the definition of the working environment, etc. Also, it determines the requirements to be accomplished by the robot based on the proposed construction technologies.
2. Conceptual design, where the robot is designed conceptually in order to check if the performance specifications can be reached.
3. Experiments using computer-graphics simulation. This stage is unique to the proposed development process as it facilitates the testing of the alternatives needed to optimize SHAMIR's selected parameters. It has the three following objectives:
   - To perform functional feasibility tests of the various suggested systems.

- To compare the performance of alternative systems
- To determine the optimal values of the robot's parameters

4. Detailed design
5. Prototype construction

SHAMIR is designed as a multipurpose robot to operate inside large halls. As an implementation of SHAMIR, a construction technology, terrazzo tile floor was simplified at the conceptual stage. The conventional method of terrazzo tile flooring consists of spreading sand, spreading mortar, and setting the tiles. The proposed solution is to set the tiles directly on the top of the concrete floor, using bonding materials such as glue. The modification in the construction technology resulted in simplifying the conceptual design of the SHAMIR.

5.6 COMPLEXITY AND RECOMMENDATIONS IN CONSTRUCTION ROBOTS DESIGN

There are several ways of designing construction robots. One approach to accomplish a robot design is to mimic a human worker without any change in the manual construction technology (Navon, 1995). This approach is typical to robot developers who are not familiar enough with construction technologies. For example, a masonry robot that lays the bricks and bonds them with mortar. There are two disadvantages of this approach. First, the robot will most likely be too complex. Second, the cost of such robot will probably be unjustified. Another approach is to modify a construction technology so it can be performed with minimum changes to commercially available robots. Likewise mimicking human workers, this approach may be costly because the changes to construction technology may involve very expensive solutions.

An intermediate approach is to bring construction and robotics technologies closer together (Navon 1995, Slaughter, 1997). This approach will require changes to robot design and the way we do construction today. Successful changes may result of valuable implementation of robotics in construction. Moreover, design and construction processes of a facility need to be connected in some way (Slaughter, 1997). This connection may influence the acceptability of these technology applications during the design process.

Explicit analysis and the integration of either advanced construction technologies or traditional methods within the earliest conceptual design stages of a facility, may lead to new concepts of building systems and new structural systems. "New systems that are designed with the ease of automation in mind may also improve aspects of the construction process even without automation" (Slaughter, 1997)

5.7 A MAN-MACHINE-SYSTEM (A MOBILE BRICK LAYING ROBOT)

Pritschow et al. (1996) discusses the technological aspects involved in the development of a mobile bricklaying robot. The tasks of mobile bricklaying mobile include picking bricks from prepared pallets, the application of bonding material and the erection of brickwork at high accuracy and quality. The proper function of the robot requires; handling different sizes of brick, detection and compensation of material tolerances, calibration o the brick position with respect to the tool center point, automated dispensing of bonding material, and robust, site specific and cost-effective solutions.

Pritschow et al. (1996) developed a man-machine-system that enables automated onsite construction of masonry. The system consisted of a mobile robot and skilled operator. Unlike manual construction methods, onsite masonry construction requires additional planning of the construction work to achieve automation. For example, the bricks need to be pre-positioned in the planned location.

The site staff has to execute the following tasks before the actual construction:

- Plan the start location of the robot and the material.
- Supply the material.
- Erection of position reference points for the robot.
- Starting the robot.

During the construction operation the operator has the following tasks:

- To supervise the automatic construction process and correct errors that might occur.
- To supply and test material.
- To manually complete the brickwork which the robot cannot perform.

Based in a program-controlled manner, the robot can perform the following operation:

- Automated maneuvering.
- To determine the exact position using sensors.
- To locate the pallet position.
- To identify the bricks as well as pick up from the pallet.
- To apply mortar.

- Automatic positioning of the bricks with the desired accuracy.

5.8 RESEARCH AT NORTH CAROLINA STATE UNIVERSITY

Moon and Bernold (1997) developed the robotic bridge paint removal (RBPR) system at the construction automation and robotics laboratory at North Carolina State University. RBPR system was developed based on a telerobotic operation as an alternative to conventional bridge paint removal methods. This system also was developed as a safe alternative method to increase the safety of the workers and to protect the natural environment against toxic pollution. Telerobotic approach frees the workers from exposure to the toxic lead paint by separating the workers at a control station from the operational mechanism at the work area.

The telerobotic operation of bridge paint removal uses two control strategies to accomplish the necessary tasks to remove the paint. The first strategy is to visually inspect the steel beam surface, define the corroded area, and to setup and position the RBPR under the bridge. This operation is controlled manually by a human operator using a joystick and with the aid of a visual live image from a camera and a sensory data. The second strategy is to perform the actual paint removal work using the end-effector positioned at a desired location. This strategy involves generating an automatic motion path for the robot arm to spot- clean the paint. Subsequently, the robot arm moves to the required position and performs the operation.

“By regulating the dynamic interaction between the operator and the robot controller, supervisory control permits performance that either autonomous controller or human operator alone would be able to achieve” (Moon and Bernold, 1997). The developed telerobotic RBPR demonstrates that the manual control capability is of great importance for tasks that have high complexity. The control of the RBPR system keeps the human operator as a supervisory integral part of the overall control system.

5.9 CONSTRUCTION PROCESS SIMULATION WITH RULE-BASED ROBOT PATH PLANNING

Stouffs et al. (1994) developed a rule-based simulation program (RUBICON) for application to building construction. The RUBICON simulator requires a specified task schedule to generate and simulate a motion path for each robot action, avoiding obstacles, safety, and other considerations (see Figure 5.1).

The input to the RUBICON program consists of two kinds of files:

1. The task plan file consisting of:
    - Description of the construction elements.
    - The construction process as a sequence of tasks. Tasks either performed by human or robot crew. A typical robot task may be: “Move Wall Panel Mark 1, Floor 1, and Part #5 (WALL-PANEL-1.15) from truck site (0.0, -4.0, 2.0) to position x-y-z (54.4, 6.6, 1.2) with the Robot overhead Crane. Estimated time is 0.16” Stouffs et al., 1994).
2. The motion file, consisting of:
    - Description of the motional capabilities of the robots characterized by their ability to lift, move, and place construction elements from a fixed location to a placement location.

- The motion rule set of the robots behavior.

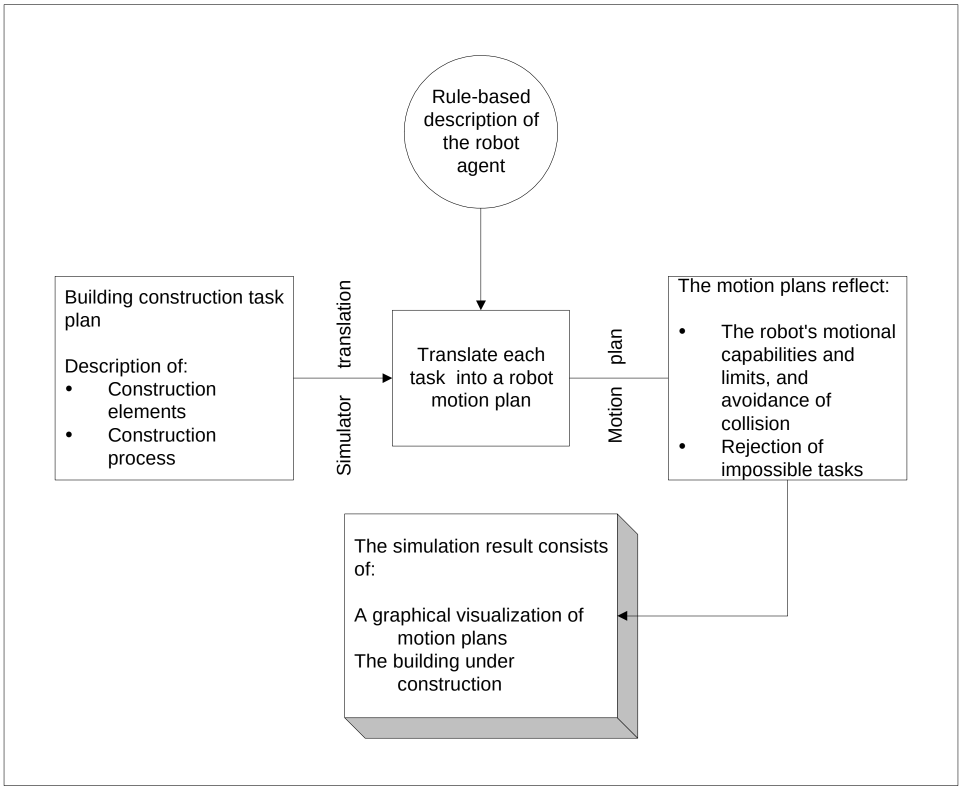


Figure 5.1: RUBICON simulation process (Stouffs et al., 1994).

The result of RUBICON simulation consists of graphical visualization of a sequence of construction processes as pre-described in the task plan file, and the motion of the robots as pre-described in the motion file (Stouffs et al., 1994).

RUBICON incorporates within itself an automatic rule-based planner that returns a path for each action. It can reject impossible tasks, can simulate crane placement alternatives, and can simulate influences on productivity of human and robot crew interaction. However, RUBICON doesn't have the visual capabilities to interactively simulate a construction process because it is based on predefining the construction process and the corresponding tasks prior to running the simulation. Interactivity here refers to the user's ability to visually execute construction tasks with simultaneous feedback.

5.10 HUMAN, TOOLS AND EQUIPMENT

5.10.1 DIVISION OF WORK BETWEEN HUMAN AND EQUIPMENT

To take human, tools and equipment into a common taxonomy, it is first necessary to analyze human, equipment, and work tasks to determine how they interact among each other. This section reviews the division of work between human and equipment. Given that the goal of work division is to enable modeling and improving construction operations, it is important to examine carefully what type of work human should do and when machine might be chosen instead. This will require exploiting the abilities of both human and equipment.

As shown in Table 5.2, Singleton (1974) outlined some characteristics that distinguish human performance from that of machines on a number of functions. Depending on the task, it is sometimes better to use equipment than human. Equipment is obviously good at tasks requiring power, speed, and computing. Moreover, equipment is much better than human in handling tasks that require extensive physical work, and can sometimes handle the information processing work.

Table 5.2 also shows that humans are superior at information intensive operations such as adapting, judging, and sensing, while machines are better at physical, repetitive operations. Furthermore, as a step toward improvement of construction operation, equipment and tools should be further analyzed. An example of this is the improvement to a screwdriver. Conventionally, when a screw is used to connect two parts, the usual procedure is to go grab the screw, start it in the hole, and then tighten it with a screwdriver. This operation was simplified by attaching a tool that would grab the screw and link it to the screwdriver while you start it in the hole.

Table 5.2: Relative advantages of human and equipment: adopted from Singleton (1974).

Property	Advantages and disadvantages	
	Man	**Equipment**
Speed	Slow speed with reaction time lag	Much superior
Power	0.2 hp for continuous work; maximum 2hp for 10 sec	Large, unchanging power available
Consistency in routine, repetitive work	Subject to fatigue and lack of motivation	Ideal
Simultaneous activities	Single channel with low information processing capabilities	Multi –channel
Computing	Slow and inaccurate; good at error correction	Fast and accurate; poor at error correction
Memory	Large store, multiple access; better for concepts and strategies	Best for literal reproduction and short-term storage
Reasoning	Good inductive; easy to reprogram	Good for literal reproduction and shot-term storage
Signal detection	Can sense only a narrow band of electromagnetic signals	Can sense all electromagnetic signals
Overload reliability	Gradual breakdown	Sudden breakdown
Intelligence	Can anticipate and adapt to unpredicted situations	Incapable of switching strategies without tedious reprogramming
Manipulative abilities	Great versatility	Only specific

5.10.2 HUMAN

In construction humans control and supply most of the information processing component and some of the physical component. The physical capacity of construction workers varies from one to another due to differences in the workers' age, sex, health, and physical fitness. For example, when two skilled masons perform a brick laying operation, an older or physically unfit mason will find the operation more difficult physically than a younger or physically fit mason. Furthermore, the production of construction workers is often increased by the introduction of power-driven devices: for example, a power saw in place of handsaw.

A human usually does three things in performing any task: (1) receives information, (2) makes decisions, and (3) take actions. Information is received through his sense organs (ears, eyes, touch, etc…). Then decisions are made based on the obtained information and previous human knowledge. Decisions are then translated into actions. Actions may be purely physical or it may involve communication action (oral or written).

The first scientific efforts to apply human factors engineering to construction work is by Gilbreth in 1917 (Helander, 1981) who was originally a contractor, and applied the science of time and motion studies to masonry. He found that mason productivity could be increased by setting size and weight standards for bricks, and by limiting the height they should be lifted. Furthermore, design of workplaces and work methods seek to determine the most effective combination of the man, machine and the working environment. This could be achieved by determining which activities human can better perform and when machines are used instead. Also, by deciding how human or/and machines will do it. As listed in Tables 5.2, machines have certain abilities, which surpass human, whereas human excels machines in certain ways.

5.10.3 CONSTRUCTION EQUIPMENT AND TOOLS

Based on the distribution of physical and information processes components between human and equipment, construction equipment can be classified as: Hand tools, power-driven devices, assisted manual controlled devices, and tele-operated devices.

5.10.4 HAND TOOLS

Hand tools is the first category where both the physical (force and energy) and information components (i.e., when to start and end a task) are completely supplied by human. Hand tools do not supply any energy or information feedback. Hand tools are used to enable humans to exert a force greater than could be exerted by using muscles alone or to apply force more efficiently. Generally, manual hand tools require great human effort to use. Examples of hand tools are screwdrivers, spanners and wrenches, hammers, drill bits, clamps, measuring tapes, brushes, plumbing tools, and chisels. Also as shown in Table 5.3, hand tools extend the capability of the hand such as more grip strength, powerful impact strength, etc.

Hand tools are based on the four simple machines, where a machine is a device used to change the magnitude or direction of an applied force. The four simple machines are the lever, the pulley, the wheel and axle, and the inclined plane, as shown in Table 5.4. The screw and the wedge are also usually considered simple machines, but they are in substance adaptations of the inclined plane.

Table 5.3: Tools and the extended human capabilities.

Tools	Extended Capability
Pliers	More Grip Strength
Hammer	Impact Strength
Wrench	Torque
Drill Rpm	Speed
Fly Swatter	Reach
Gloves	Protection
Saw, Soldering Iron	Functions That Cannot Be Done With A Bare Hand

Table 5.4: The major simple machines.

Simple Machines	Definition	Tasks	Examples
Lever	A Stiff Bar That Rests On A Support Called A Fulcrum	Lifts Or Moves Loads	Shovel, Nutcracker, Seesaw, Crowbar, Elbow, Tweezers, Bottle Opener
Inclined Plane	A Slanting Surface Connecting A Lower Level To A Higher Level	Things Move Up Or Down It	Slide, Stairs, Ramp, Escalator, Slope
Wheel And Axle	A Wheel With A Rod, Called And Axle, Through Its Center: Both Parts Move Together	Lifts Or Moves Loads	Car, Wagon, Doorknob, Pencil Sharpener, Bike
Screw	An Inclined Plane Wrapped Around A Pole	Holds Things Together Or Lifts	Screw, Jar Lid, Vise, Bolt, Drill, Corkscrew
Pulley	A Grooved Wheel With A Rope Or Cable Around It	Moves Things Up, Down, Or Across	Curtain Rod, Tow Truck, Mini-Blind, Flag Pole, Crane
Wedge	An Object With At Least One Slanting Side Ending In A Sharp Edge	Cuts Or Spreads An Object Apart	Knife, Pin, Nail, Chisel, Ax, Snowplow, Front Of A Boat

When using hand tools, work is usually composed of three steps: get ready (search, select, grasp, and move), do the work, and put away (release). Based on the level of specialization, hand tools are two types: special purpose tools and multifunction tools. Special purpose tools are best for work that is repeated hundred of times, where multifunction tools, two tools in one, may eliminate processes such as reach, grasp, move, and release from the labor time. Furthermore, multifunction tools also may save the get ready and put away time. For example, a claw hammer combines a hammer and nail claw; a pliers combines a gripper and a wire cutter.

5.10.5 POWER-DRIVEN DEVICES

In this category, the machine provides some or the entire physical component to perform the work, while the human supplies some of the physical component and the all the information-processing component. An example of power-driven devices is an electric drill. The drill operator supplies some of the physical component by supporting the drill, but the motor and the drill it self supplies most of the physical work. On the other hand, the entire information-processing component is controlled and supplied by the operator. The operator guides the drill and controls the when the drill starts and stops by pressing the trigger. Likewise, a crane operator moving a steel beam from one location to the final location controls all the information components, such as identifying the beam to be moved, determining when to start and stop swinging the boom; and finally where to position/place the beam. In addition, the operator contributes partially to the physical component by using the crane controllers. In the aforementioned operation, the crane provides most of the physical component, such as lifting the beam, and moving the beam according to the operator's input. Examples of power driven devices are powered-driven saws (i.e., reciprocating, circular, and band sawing), earth-moving machines (i.e., scrapers, graders, bulldozers, and power shovels), and cranes (i.e., jib crane, derrick crane, and bridge carne).

5.10.6 ASSISTED MANUALLY CONTROLLED DEVICES

This category provides most of the physical component and some of the information-processing component to perform the work. Still the operator controls some or most of the information-processing component. Examples of assisted manually controlled devices are laser directed graders, load monitor on cranes, and automatic transmissions. Laser directed graders relieve the operator from lowering and raising the blade as the laser check the level of the blades as required.

5.10.7 TELE-OPERATED DEVICES

Similar to the assisted manually controlled devices, this category supplies all the physical work and some of the information processing input while human supplies most of the information processing input and doesn't contribute to the physical component. Televisions, videocassette recorders, and motion sensing cameras are examples of the tele-operated technology.

5.10.8 THE DISTRIBUTION OF PHYSICAL AND INFORMATION PROCESSING COMPONENTS BETWEEN HUMAN AND EQUIPMENT

Every productive construction operation that involves the use of human and equipment imposes both physical and an information component (Porter and Miller, 1985). The physically-processing component includes all the physical tasks required to perform an operation, such as force and energy. The information-processing component involves the steps required to capture, manipulate, and execute the information necessary to perform the operation. Based on the level of control and the division of the physical and information component of work between human and equipment, equipment can be categorized into four classes: hand tools, power-driven devices, assisted manually controlled devices, and tele-operated devices.

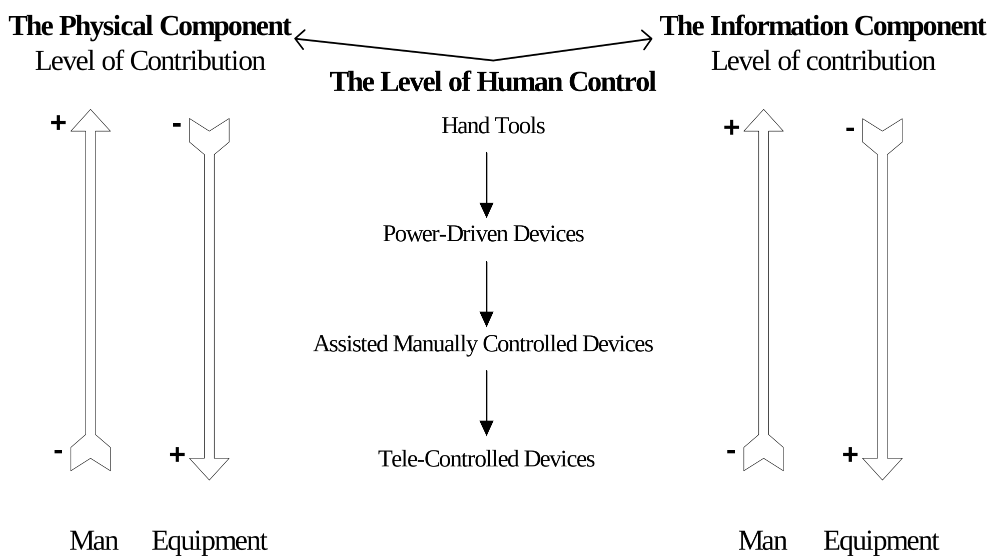


Figure 5.2: The distribution of physical and information components between human and equipment.

Figure 5.2 shows the level of physical and information contributions between human and equipment. For instance, at the hand tool level, human is the only source of input for the physical and information component. On the other hand, at the tele-controlled device level, equipment supplies all the physical work and some or most of the information input. Nonetheless, a human control involves work strategies. Work strategies determine which methods and equipment will be selected to perform a work task. For example, human may change the workload for a specific task when making a decision to select a powered control device as opposed to a hand tool.

5.11 SYNOPSIS

In this chapter, the potential uses of robotics and automation opportunities in construction are discussed. Also, the distribution of work between humans and tools and equipment based on their physical and information contributions are presented. The next chapter presents and analyses the classification of construction work at different level of detail to identify which construction operations can be usefully modeled and the appropriate level of the model.

CHAPTER SIX: TASK IDENTIFICATION

6.1 INTRODUCTION

This chapter describes and analyzes construction work classifications at different levels of detail. The analyses are focused on identifying construction operations that can be usefully modeled and the appropriate level of the model. In addition, this chapter reviews the product and process breakdowns in manufacturing operations.

Research in onsite construction operation processes has been actively carried out to identify automation opportunities. Researchers such as Kangari and Halpin (1989), Halpin and Riggs (1992), Basford and Askew (1992), and Everett (1994) have analyzed automation opportunities at various levels of detail. These levels are the task, activity, and division level. The main purpose of the analysis is to simplify the on site construction work in order to identify construction tasks that can be automated and usefully modeled. Most researchers have recognized the task level (i.e., connect, move, etc.) as the simplest and most appropriate level for automation. On the other hand, the activity level, which consists of several tasks, and the division level, which consists of several activities, becomes more complicated and probably unrealistic for a single device to complete the work.

6.2 WORK CLASSIFICATION

Warszawski and Sangrey (1985), and Warszawski (1990) investigated the performance characteristics required of robots in order to accomplish the essential construction work. Based on the performance analysis, Warszawski (1990) divided the building construction works into 10 basic tasks, as listed in Table 6.1. The basic tasks were categorized in such a way that each one of them could be executed by a single robot. Furthermore, most of the construction activities require more than one basic task for their execution. For example, the casting of a concrete element requires at least the following tasks: positioning of forms, connecting of forms, positioning of reinforcement, casting of concrete, stripping of forms, and finishing of concrete. Another example is the erection of a plasterboard partition, which requires: attaching of floor, attaching of studs, attaching of boards, jointing the boards, covering the boards with paint or wallpaper.

Table 6.1: Basic activities in building construction (Adopted from Warszawski, 1990).

Number	Task	Description	Examples of application
1	Positioning	Placing a large object at a given location and orientation	Erection of steel beams, precast elements, formwork, scaffolding
2	Connecting	Connecting a component to an existing structure	Bolting, nailing, welding, taping
3	Attaching	Positioning and attaching a small object to an existing structure	Attaching hangers, inserts, partition boards, siding, sheathing
4	Finishing	Applying continuous mechanical treatment to a given surface	Troweling, grinding, brushing, smoothing

Number	Task	Description	Examples of application
5	Coating	Discharging a liquid or semiliquid substance on a given surface	Painting, plastering, spreading mortar or glue
6	Concreting	Casting of concrete into molds	Casting of columns, walls, beams, slabs
7	Building	Placing blocks next to or on top of one another with a desired pattern	Blocks, bricks, or stones masonry
8	Inlaying	Placing small flat pieces one next to the other to attain a continuous surface	Tiling, wood planks, flooring
9	Covering	Unrolling sheets of material over a given surface	Vinyl or carpet flooring, roof insulation, wallpapering
10	Jointing	Sealing joints between vertical elements	Jointing between precast elements, between partition boards

Table 6.2 shows a typical breakdown structure of construction work by Guo and Tucker (1993). As an illustration, they have proposed a division of concrete work at the division, activity and task level.

Table 6.2: Area-activity-task example (Guo and Tucker, 1993).

Division	Activity Level	Task level
Concrete	Rebar fabrication	1. Bend
		2. Position
		3. Tie
	Concrete placement	1. Spread concrete
		2. Vibrate
		3. Finish

Guo and Tucker (1993) suggested a comprehensive breakdown of construction activities into their construction tasks level. Again the purpose of the breakdown structure of construction work is to identify automation opportunities. They identified and defined forty-two construction tasks, as a listed in Table 6.3.

Table 6.3: Basic tasks involved in construction activities (Guo and Tucker, 1993).

	Basic Task	Definition	Examples
1	Arrange	Put a number of objects in a proper order	Arrange rebar
2	Align	Keep objects in a straight line or orientation	Align steel columns
3	Bend	Deform the shape of an object	Bend steel rebar
4	Caulk	Inject sealant between two adjacent objects	Seal concrete joints
5	Clean	Remove unwanted dirt, material or impurities	Sweep floor
6	Coat	Apply a layer of liquid on an object's surface	Paint wall
7	Communicate	Talk or use hand signals to transfer information	Ask or answer
8	Compact	Condense soil or other material	Compact soil refill
9	Connect	Join or fasten two objects to each other	Nail, bolt, tie, weld
10	Cover	Unroll sheet material on an object's surface	Unroll carpet
11	Cut	Divide one object into two or more pieces	Saw wood, cut tile
12	Disconnect	Break the connection between two objects	Strip forms, unbolt
13	Dismantle	Demolish or break down an undesired portion	Dismantle concrete
14	Drill	Make a hole by rotation	Drill hole
15	Excavate	Dig out by remove soil or material	Excavate tunnel
16	Fill	Put soil or material in place	Dump soil
17	Finish	Apply continuous mechanical treatment to surface	Trowel, grind
18	Hit	Strike hardly to push an object	Hit piles
19	Hold	Keep an object in a position temporarily	Hold hose, tag line

	Basic Task	Definition	Examples
20	Identify	Recognize an appropriate member	Identify steel column
21	Inlay	Set small flat pieces next to each other	Set tiles
22	Insert	Push an object into another one	Insert from ties
23	Inspect	Examine and detect flaws or verify correctness	Visually check
24	Install	Put and object into final position	Install light fixture
25	Level	Keep material on a horizontal plane	Screed concrete
26	Lift	Move an object upward for transporting	Lift concrete panel
27	Lay	Set objects next to or on top of each other	Lay bricks
28	Measure	Determine or layout correct dimensions	Measure rebar layout
29	Operate	Control an equipment for work	Operate crane
30	Position	Move an object to the correct location	Position steel beam
31	Pour	Cast concrete into forms or slabs	Pour concrete slabs
32	Prepare	Make material ready for future use	Get material
33	Pull	Draw electrical wire through conduit	Pull cable
34	Pump	Transport material by air pressure	Pump concrete
35	Roll	Move an object on wheels along surface	Roll the flooring
35	Shape	Modify the shape of an to fit into position	Trim wood
37	Spray	Jet liquid of particles without contact with surface	Spray paint
38	Spread	Apply semi-liquid material to various location	Spread mortar
39	Tap	Strike or touch an object gently	Tap tiles or bricks
40	Transport	Move material to designated location	Transport bricks
41	Vibrate	Shake or tremble to consolidate material	Vibrate concrete
42	Write	Make a note or mark to indicate a specific purpose	Write notes

6.3 TASK IDENTIFICATION

The work of Everett (Everett, 1994) addressed issues facing the construction industry and some of the strategies for handling them. Everett's work focused on the development of an automation technology and the potential for solving problems of productivity, safety, quality, and skilled labor shortages. "The most important step in developing automation technology is selecting appropriate tasks to automate" (Everett, 1994). Everett developed a hierarchical classification to divide construction field operations into several levels as shown in Table 6.4, of which the basic task level is appropriate for construction automation.

Table 6.4: Classification of construction field operations (Everett, 1994).

Level (1)	**Description (2)**	**Examples (3)**
1	Project	Petrochemical plant, office building
2	Division	Concrete, masonry, mechanical
3	Activity	Drywall partition, concrete wall
4	Basic Task	Connect, cut, measure, position
5	Elemental Motion	Reach, grasp, eye travel
6	Orthopedics	Muscle, bone, joint
7	Cell	Muscle fiber, nerve

Everett (1994) divided the construction project into seven levels: project, division, activity, basic task, elemental motion, orthopedics, and cell. The basic task level was identified as the most critical level for construction automation. Each of the basic tasks represents one of the steps performed in the field to do an activity. The basic tasks shown in Table 6.5 are connect, cover, cut, dig, finish, inspect, measure, place, plan, position, spray, and spread (Everett, 1994).

Everett's system classified construction equipment into four categories (Table 6.6) based on the distribution of physical components and information components between man and machine. The four categories are tools, power tools, automatic tools, and robots

Table 6.5: Basic tasks (Everett, 1994).

Basic Task (1)	**Definition (2)**	**Examples (3)**
Connect	Join or attach components together	Screw, nail, bolt, staple, weld
Cover	Spread or overlay sheet material over surface	Unroll carpet or single ply roofing
Cut	Penetrate or separate with sharp edge	Saw wood, cut drywall, drill hole
Dig	Loosen, remove, or move soil	Excavate trench, backfill
Finish	Apply continuous mechanical treatment	Grind, bushhammer, sand, rub
Inspect	Examine critically to identify flaws or verify correctness	Read level, verify alignment of machinery
Measure	Determine or lay out dimensions	Mark drywall, lay out track
Place	Move small object to specified location and orientation	Set tile, lay brick, align conduit
Plan	Gather information, think about upcoming work	Read blueprints, formulate work sequence
Position	Move large object to specified location and orientation	Erect steel beam, lift drywall
Spray	Direct jet of liquid or particles, no contact with surface	Spray paint, sandblast
Spread	Distribute liquid or paste material	Paint with brush, cast concrete

Table 6.6: Distribution of physical and information components of work (Everett 1994).

Hardware (1)	**Physical input** (2)	**Information input** (3)	**Examples** (4)
Tool	Human	Human	Hammer, screwdriver
Power tool	Machine/human	Human	Jackhammer, electric drill
Automatic tool	Machine/human	Human/machine	Automatic transmission
Robot	Machine	Machine	SSR-3 (Fireproofing Spray Robot)

Some of the basic tasks listed in Table 6.5 were adopted from Warszawski and Sangrey (1985) and Warszawski (1990). Whereas Warszawski and Sangrey (1985) describe several basic activities which “were defined in such a way that each of them could be performed by a single robot,” Everett (1991) describes the basic tasks beyond the specific examples of basic activities for robots. “Basic tasks are the fundamental building blocks of construction field work, each representing one in a series of steps that comprise an activity” (Everett, 1994). The developed taxonomy in this research adopted and refined Everett’s basics tasks. While Warszawski and Everett refer to the most appropriate level of modeling construction operations as the basic task level, the developed taxonomy refers to it as the operation level. A full description of the developed taxonomy is provided in the next chapter.

6.4 ILLUSTRATION OF WORK CLASSIFICATION

To illustrate the structure of work classification, the following scenario is considered for the activity, install drywall. At the activity level, the activity install and finish a drywall would normally consists of a sequence of separate construction operations that are normally performed by one or more crewmembers. Some other activities, such as the construction of the framing members to which the drywall will be connected, need to be completed before the starting of activity install drywall. Once the framing crew members finish their work, another crew starts installing the drywall panels. Finally, another crew begins finishing the joints. Of course the three activities are related, but the framing task is a separate operation from installing drywall as well as finishing the joints. As Everett (1994) described, at the basic task level, the activity, install drywall is broken down into four basic tasks that one or more crew members would normally perform: (1) measure the wall and mark the drywall panel; (2) cut the drywall panel to the correct size; (3) move the panel into position; and (4) connect the panel to its final location (the framing members).

6.5 MANUFACTURING OPERATIONS

This section reviews how industrial process engineers distinguish between one act and another in breaking down a task into its constituent processes. Industrial process engineers are responsible for the tasks and the constituent processes that are performed on a project. This responsibility consists of process definition, planning, performance, evaluation, and improvement. In manufacturing, a process may relate to a design process, a manufacturing process or work process.

In manufacturing, there are two types of production operations: processing operations and assembly operations (Prasad, 1996). Processing operations are those activities that transform a component from one state of completion to another advance state of completion, while assembly operations join two or more components together. Processing operations can usually be classified into one of the following four categories: basic processes, secondary processes, operations to enhance physical properties, and finishing operations. Both processing operations and assembly operations require most of the following inputs: raw material, equipment, tooling and fixtures, energy, and labor.

6.6 INDUSTRIAL PROCESS BREAKDOWN

The industrial process engineer determines the techniques and a time standard in association with each production task. The objective of determining the work techniques is to identify the best approach to perform the task. Work techniques involved in determining the manufacturability of the work components. For example an L-shape metal component may be machined, or cut to its shape, or welded together from sub-components. Time standard is used determine how much time the task should take. Each task is often associated with a component.

One of the issues that is considered during the breakdown of tasks is process planning. Process planning involves in determining the sequence of each production operation. It also links the production operations with their associated machines or tools for a particular component.

The main goal of breaking down a task or production operation is to simplify and divide the job into components and processes. A production operation could be broken down into its smallest reasonable work components. A reasonable work component is the practical set of processes into which a task can be divided. In production operations, drilling a hole is an example of the smallest reasonable work component. Furthermore, the joining of two components together with a screw and nut is another example of the smallest reasonable work component in assembly operation.

The breakdown of a task into its constituent processes involves three essential elements: work breakdown structure (i.e., the layout of the workstations), product breakdown structure (i.e., the product components), and process breakdown structure (i.e., the sequence of tasks or processes). The aforementioned elements are interrelated. The product breakdown structure provides the knowledge about the product, while the process breakdown structure forms and describes the process, and the work breakdown structure organizes and defines the works (Prasad, 1996).

A work breakdown structure (WBS) "is a series of interrelated work tasks initially set in motion by the planning track." (Prasad, 1996) The WBS describes the structures associated with organization and management of work tasks. Typically, a WBS contains three major categories: teams (for example, people, machines, and facilities), tasks (such as, the work activities, information to about the activities, and any other information to accomplish an activity), and time schedule.

The product breakdown structure (PtBS) is "the decomposition of a complex system into a set of hierarchical structure" (Prasad, 1996). The system could be decomposed hierarchically into subsystems, components, parts, material/attributes/features/ parameters, and finally common representation and standards (see Figure 6.1).

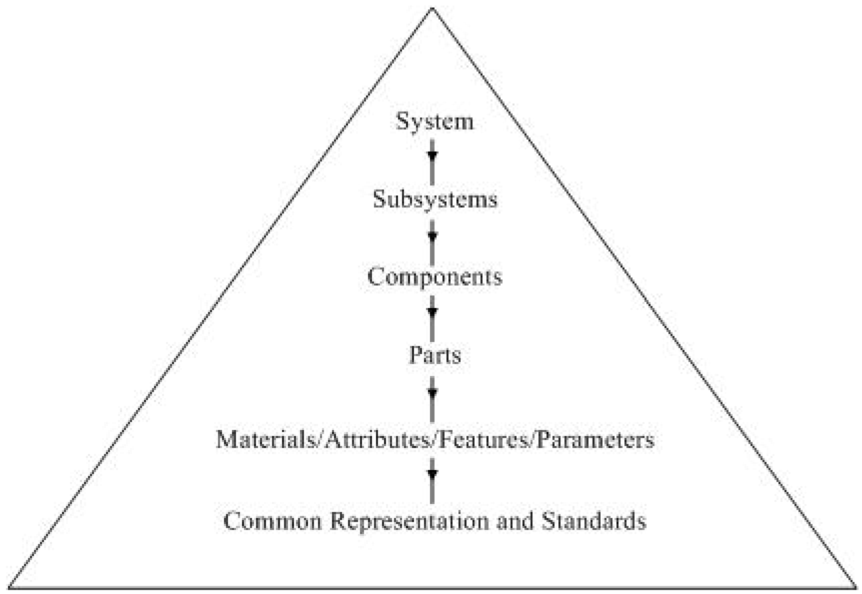


Figure 6.1: Hierarchical decomposition of products (adopted from Prasad, 1996).

Process breakdown structure (PsBS) is a fundamental approach to handling complex processes. In its simplest sense, PsBS "is the manner in which a company designs and manufactures its products" (Prasad, 1996).

Another issue that the industrial process engineer considers during the breakdown of a task is dependency and the order in which the work components can be accomplished. Almost, in every processing or assembly operation, there are precedence requirements that define the sequence in which the operation can be performed.

The breakdown of a task into subtasks and its constituent process requires the process engineer to takes into consideration how the constituent processes will be related. According to Prasad (1996), there are four distinct ways such processes can be related:

dependent processes, semi-independent processes, independent processes, and interdependent processes.

Dependent processes: A pair of processes where one process (say Process_A) requires a complete or partial transfer of the output information from another process (say Process_B). In general, complete transfer of information makes processes run in a series. Process_B is dependent on Process_A (see Figure 6.2).

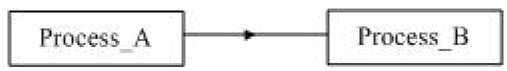


Figure 6.2: Dependent processes.

Semi-independent processes: Where the transfer of output information from one process to the other is only a partial transfer. Therefore, a weak interaction exists between a group of processes. For example, partial output information from Process_A and Process_B are necessary to complete Process_C. Process_C is semi-independent of Process_A or Process_B (see Figure 6.3).

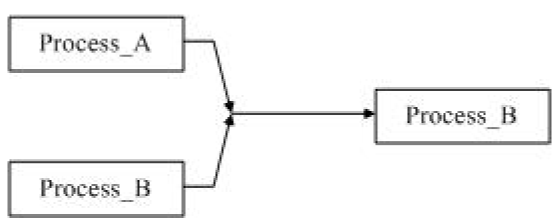


Figure 6.3: Semi-independent processes.

Independent tasks: Where no portion of the output information from one process or the other is required for the completion of both processes. Process_A is independent from Process_B (see Figure 6.4).

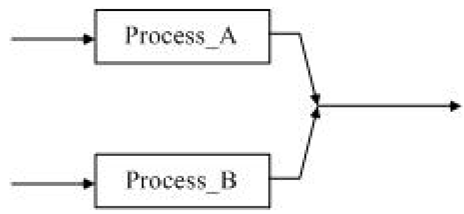


Figure 6.4: Independent processes

Interdependent processes: Where a two-way transfer of output information is required for the completion of any process. Information from Process_A is used to complete Process_B and the information from the Process_B is used to complete Process_A. Process_A and Process_B is interdependent (see Figure 6.5).

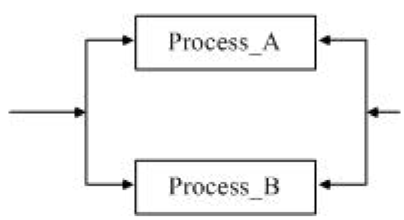


Figure 6.5: Interdependent processes

Similarly, each type of construction work can be classified in term of its own components and processes. For instance, the erection of steel structures can include the following processes: lifting, measuring, cutting, drilling, sub-assembly, surface finishing, painting, and inspection. Processes can be related as described by Prasad (1996). For example, the process of cutting is dependent on measuring, sub-assembly is semi-independent on surface finishing and painting, drilling is independent from cutting, and sub-assembly and lifting are interdependent on each other. In the case of interdependent processes, the crane lifting and reach capabilities might affect the practicality of using of sub-assembled structures and visa versa.

6.7 SYNOPSIS

Chapter Six presents and analyzes construction work classifications at different levels of detail. The main purpose of the analyses is to identify which construction operations can be usefully modeled and the appropriate level of the model. Therefore, various classification methods that are used to identify automation opportunities in construction are examined. In addition, the product and process breakdown structures in manufacturing operations are reviewed.

CHAPTER SEVEN: COMMON TAXONOMY

7.1 INTRODUCTION

The main purpose of the developed taxonomy is to provide a classification structure that will bring about the development of a common construction modeling language. The common construction language is the root source of the proposed modeling system, which ultimately will be used to record, analyze, and improve the way we do construction today.

The construction modeling taxonomy is constructed by looking in the ways that in-field construction activities respond to the eight basic operations (after Everett, 1994): connect, cover, cut, finish, inspect, measure, move, and plan. Everett's basic tasks include *place* and *position* tasks. In the developed taxonomy, those two basic tasks were replaced with the "MOVE" operation. Also, the *cut* and *dig* basic tasks were combined into one operation "CUT". Finally, the *finish*, *spread*, and *spray* basic tasks were combined into one operation "FINISH".

The developed taxonomy doesn't present the only possible taxonomy of construction modeling, and none of the examples used in this research are likely to be the best examples for construction modeling. However, the developed examples and the taxonomy do show that, far from being just a new way to present construction modeling, the developed modeling system is a common construction language that can be used to record, analyze, and improve construction operations.

7.2 THE TAXONOMY

The developed taxonomy identifies a hierarchical representation for construction projects based on the operational consideration shown in Figure 7.1 and Figure 7.2. The hierarchy consists of seven levels: product, assemblies and subassemblies, components, operations, processes, physics, and control. A product is defined in terms of assemblies and subassemblies, which are collection of construction components. A component is realized through collection of operations, which are the end result of collection of processes. Physics and controls are readily identifiable components of a process.

7.2.1 THE PRODUCT

The first level in the hierarchy is the product. The taxonomy refers to construction projects as products. Whether the product is a building, bridge, dam, pipeline, or any one or numerous other types of products, it consists of a number of construction assemblies and subassemblies that are linked by well-defined, but not necessarily known relationships, and joined together with the aid of a process performer. A process performer could be a human, tool, or equipment that follow a process to perform an operation.

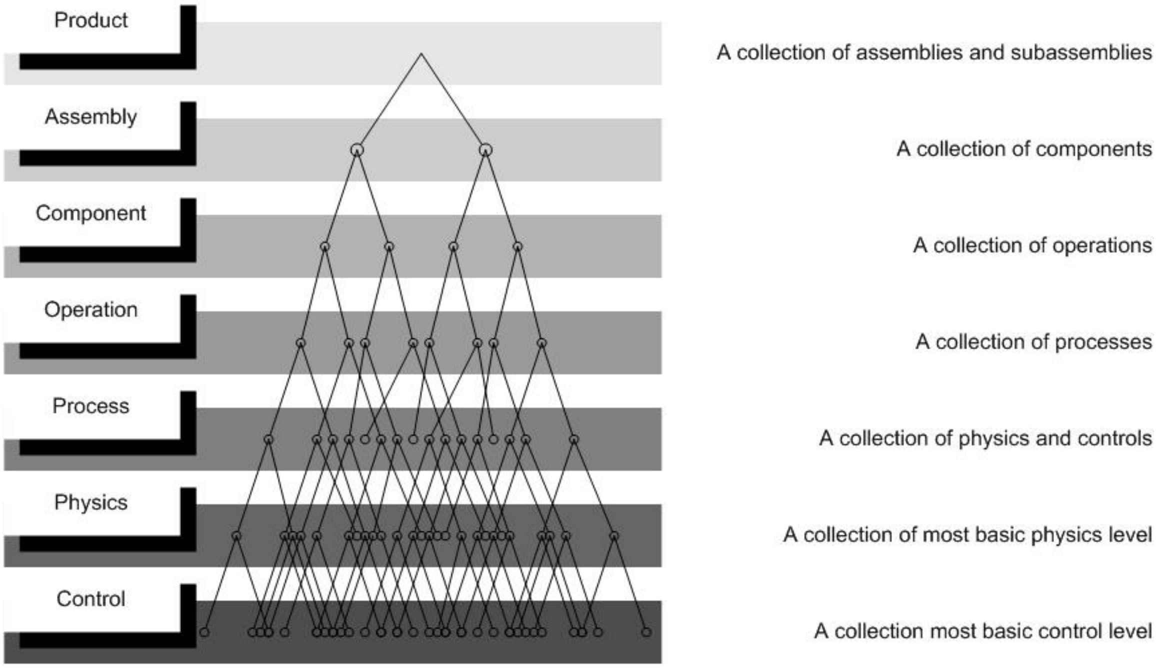


Figure 7.1: The hierarchical representation for construction projects.

The nature of construction products is unique in several aspects. The product is usually one of a kind facility, individually designed and built, in a relatively short-time frame. Decision at this level relates to the breakdown structure of the product into assemblies and subassemblies as well as the alternative production methods.

7.2.2 ASSEMBLIES AND SUBASSEMBLIES

The assembly level represents a breakdown structure of a construction product into major assemblies and subassemblies. An assembly is a group of two or more subassemblies that can be brought together. A subassembly is the collection of two or more construction components that can be joined together. For example, a steel structure assembly involves a variety of basic structural components such as beams, columns, plates, and pipes joined in subassemblies.

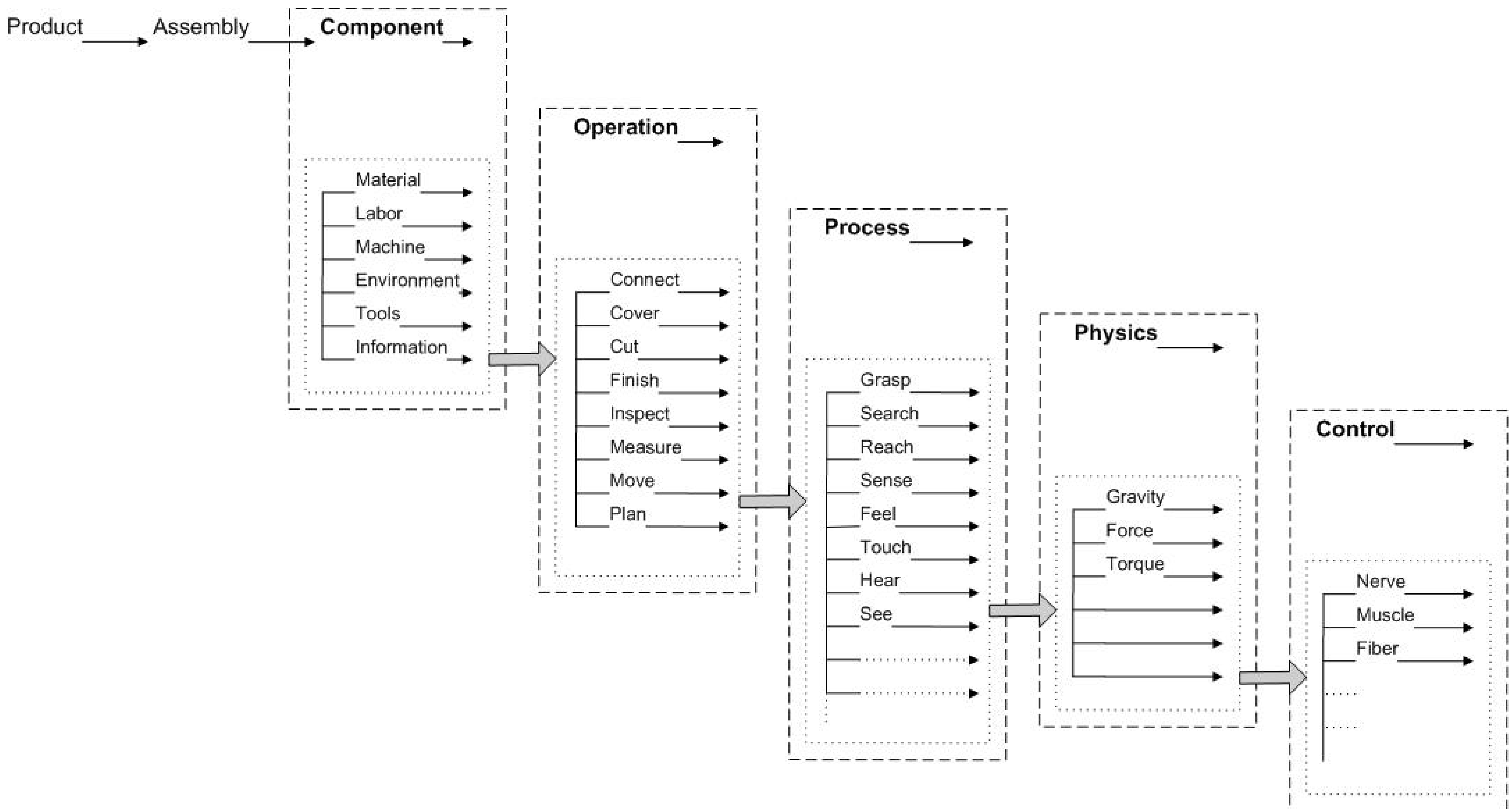


Figure 7.2: Taxonomy of hierarchy.

7.2.3 COMPONENT

The component level represents the general building materials. It includes the size, shape and characteristics of materials. Examples of components are brick veneer, studs, insulation material, etc.

Resources such as, labor, tools, machine and the surrounding environment were added to this level. Information about material, labor, machine, tools, and the working environment are included at the component level.

7.2.4 OPERATION

Most construction operations are composed of human individuals, equipment, and materials. This level is concerned with the technology and details of how operations are performed and represented. The operation level can be described as the end result of collection of processes and covers the breakdown structure of most on-site construction operations. The taxonomy defines a standard operational system that provides a limited number of reusable construction operations.

The standardized construction operations and their descriptions are shown in Table 7.1. The "CONNECT" operation is the operation used to connect components or assemblies together like welding and nailing. "COVER" is the operations for spreading or overlaying material over the object's surface e.g. vinyl or carpet flooring. The "CUT" operation is the operation used to divide or separate one object into two or more pieces. The "FINISH" operation is the operation used to apply continuous mechanical treatment to a surface. The "INSPECT" operation is the operation used to examine and detect flaws or verify correctness. The “MEASURE” operation is the operation used to determine or layout correct dimensions. The “MOVE” operation is the operation used to relocate an object to a correct position and orientation. The “PLAN” operation is the operation used to gather information and to plan upcoming work.

Table 7.1: The standardized construction operations.

Operation	Definition	Example
CONNECT	Join two objects to each other	Nailing, bolting, tying, welding, taping, adhering
COVER	Unrolling sheets of material over a given surface	Vinyl or carpet flooring, roof insulation, wall papering
CUT	Divide, separate, one object into two or more pieces	Sawing wood, cutting tile, excavating, digging, drilling, piling
FINISH	Apply continuous mechanical treatment to a given surface	Sanding, rubbing, grinding, spraying, painting, brushing, casting concrete, plastering, smoothing, troweling
INSPECT	Examine and detect flaws or verify correctness	Visual inspection
MEASURE	Determine or layout correct dimensions	Measure rebar layout
MOVE	Relocate an object to correct position and orientation.	Relocate, pump, transport, place, position, pour
PLAN	Gather information, think about upcoming work	Read blue prints, order material, write notes, formulate work sequence

7.2.5 PROCESS

The process level consists of a relatively few fundamental work processes, which are performed over and over again to complete an operation. This level involves micro modeling and analysis of a set of motions and actions that is executed by human and/or equipment. Examples of work processes are search, select, grasp, hold, etc.

7.2.6 PHYSICS AND CONTROL

At the physics level humans and equipment are analyzed, with their abilities and limitations, to determine their capabilities to perform work according to the laws of physics, mechanics, etc. For humans, this level is concerned with the motions of human body and the forces that cause those motions. In this sense, it relies upon the second law of classical Newtonian mechanics.

The control level focuses on both the human control system and the machine automatic control system. This involves static muscle force control and dynamic muscle velocity control. It also represents a set of interacting anatomical elements (sensory organs, nerves, muscles, and bones) that perform physiological functions, which operate according to biophysical laws (Phillips, 2000).

7.3 THE TAXONOMY OF CONSTRUCTION OPERATION KNOWLEDGE

Figure 7.3 summarizes the main structure of the taxonomy of construction knowledge. The taxonomy of construction knowledge consists of six major blocks of knowledge whereas the knowledge of construction operation is the core block. The six major blocks depend on each other. Thus any value from one block can be shared with almost any value from another block, resulting in a large number of variables. The knowledge of physical input and the knowledge of information input are directly related, especially in the case of modeling the level of human/machine control for a given construction operation. Similarly, the knowledge of the product breakdown structure and knowledge of the process breakdown structure are combined on one axis. In this composition, the process sequence makes sense only if the product breakdown structure is defined. The last axis combines the knowledge of available resources and the knowledge of construction operations. It is defined as the core block.

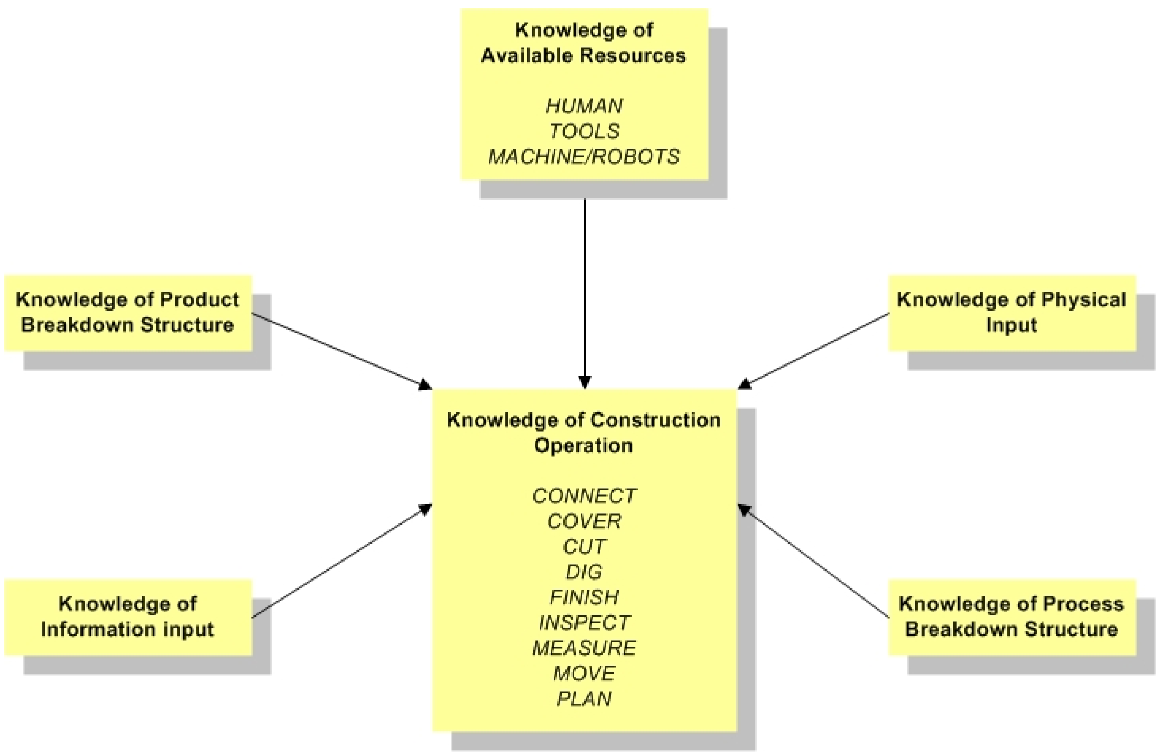


Figure 7.3: The six major blocks of construction operations knowledge

The core block is mainly defined by eight major construction operations. Let us consider a simple example, the operation “CONNECT” steel beam 1 to steel column 1. Before it can be executed, several questions must be initiated and answered. These questions come from the blocks of construction operation knowledge, such as, “which steel beam and steel column will be connected to each other?” The answer to this question comes mainly from the knowledge of product breakdown structure.

The next question is “how to connect the two parts together?” The knowledge of process breakdown structure provides part of the answer to this question by presenting a sequence of processes that leads to the realization of the connect operation. Subsequently, it initiates the following question: “who is going to connect the two parts together?” At this level, the knowledge of available resources, the interface between human, tools, and machine is presented and the question is answered accordingly. The designer of the operation should make the decisions based on best practices or develop his own combination of human/tool/machine interface to answer the aforementioned question. The interface between human, tools and machine is based on the level of shared physical and information input for any given operation.

Additional questions such as “do the physical constraints support this operation?” What are the physical properties of the steel beam? The answer to these questions comes directly from the knowledge of physical input and from the physics level as described in the developed taxonomy.

Furthermore, the main goal of the developed taxonomy is to provide the overall breakdown structure of construction operations, construction objects, their physical behavior and information exchange across the defined blocks of construction operations knowledge.

7.4 THE DEVELOPED TAXONOMY VS. THE IFC AND AECXML STANDARDS

The Industry Foundation Classes (IFC's) and aecXML schemas are two complementary means for exchanging information within the AEC community (IAI, 2003). The IFC's and aecXML are developed by the International Alliance for Interoperability (IAI). The main goal of the IAI is to facilitate interoperability and exchange information among project participants throughout the lifecycle of a facility by direct communication between software applications.

In general, IFC's are used to model "things", while aecXML is for talking about things. AecXML can be used to agree what "door" means, but it won't describe doors or model them.

This section reviews both standards and compares them to the developed taxonomy. The main goal of the comparison is to show the distinct capabilities of the developed taxonomy to model construction operations.

7.4.1 IFC'S STANDARDS

IFC's were developed to provide building data models from the computer application used by one participant to another within the AEC domain; with no loss of information. IFC's are defined by IAI as data elements that represents the parts in a constructed facility, or elements of the processes, and contain the relevant information about those parts. IFC's can be used electronically to produce an electronic project model of the constructed facility that contains all the information of the parts and their relationships to be shared among project participants. The project model constitutes an object-oriented database of information shared across participants and continues to grow through out the life cycle of the constructed facility.

The IFC-Model has a layered, hierarchical structure for the development of data components. As shown in Figure 7.4, the IFC Model Architecture consists of the following conceptual layers: Resource layer, Core layer (Kernel and Extensions), Interoperability layer, and Domain/Applications layer.

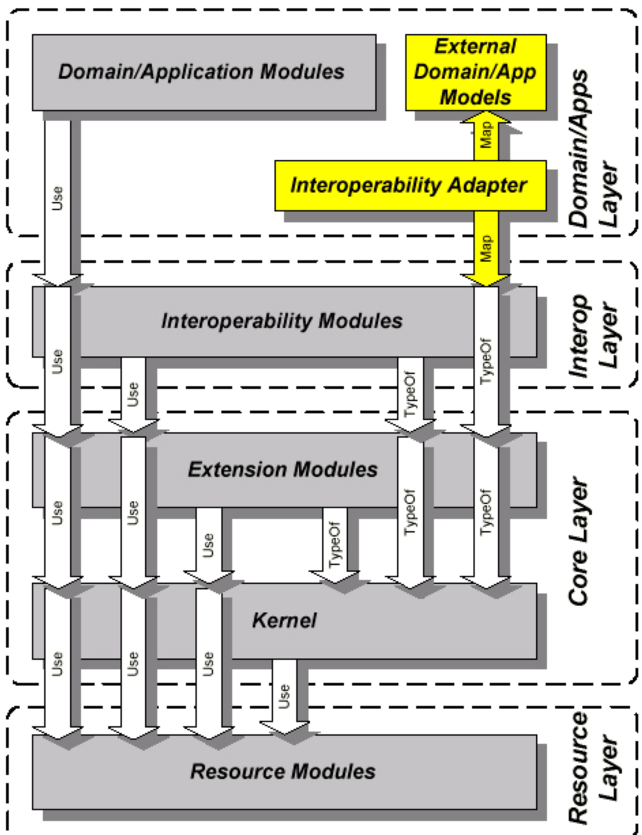


Figure 7.4: The layering concept of the IFC architecture (IAI, 2003).

The hierarchy structure is based on a ladder principle. At any layer, a class may reference a class at the same or lower layer but may not reference a class from a higher layer. For example, Resource classes may only reference or use other Resource classes. Resource classes may not reference classes from the Core layer.

The Resource layer (shown at the bottom of Figure 7.4) provides resource classes used by classes in the higher levels, such as the core layer. Within the Resource layer the following schemes are included (IAI, 2003):

IfcActorResource: This scheme defines the properties of persons and organizations whose services may be used within a project.

IfcClassificationResource: This scheme defines the assignment of classifications to objects.

IfcCostResource: This scheme provides the means to identify the cost of an object or aggregation of objects.

IfcDateAndTimeResource: This scheme defines dates and times that may be applied.

IfcDocumentResource: This scheme defines object types related to the documents and document management.

IfcGeometryResource: This scheme specifies the resources for the geometric and topological representation of the shape or a product.

IfcMaterialResource: This scheme contains the types and classes which are used to define and manipulate materials and their properties.

IfcMeasureResource: This scheme specifies units and measures that may be assigned to quantities.

IfcPropertyResource: This scheme defines a set of basic property objects that can be associated with IFC objects through the IfcPropertySet.

IfcRepresentationResource: This scheme defines the representation of shape and topology as important definitional properties for products defined within the IFC object model.

IfcUtilityResource: This scheme deals with general concepts such as identification, ownership, history, and tables.

The Core layer provides a Core project model that contains the Kernel and several Core Extensions. Within the Core layer the following schemes are included:

IfcKernel: This scheme defines the most abstract part of the IFC architecture. It handles the basic functionality, relative location of products in space, sequence of processes in time, or general-purpose grouping and nesting mechanism.

IfcControlExtension: This scheme defines basic concepts for capturing controls related to any object in the IFC model derived from IfcObject.

IfcModelingAidExtension: This scheme defines basic object concepts used as aids in the development of the project model, particularly those related to geometric placement and alignment.

IfcProcessExtension: This scheme captures information concerning the work and construction resources uses in the process required in order to create a product.

IfcProductExtension: This scheme defines basic objects concepts such as Building, Site, and Space.

IfcProjectMgmtExtension: This scheme defines basic concepts used in the project management processes.

The Interoperability layer provides a set of modules defining concepts or objects common across the AEC industry domains. Within the Interoperability layer the following schemes are included:

IfcSharedBldgElements: This scheme covers the definition of building elements that are shared among several IFC domain or application type models.

IfcSharedBldgServiceElements: This scheme includes concepts such as equipment, fixture, and electrical appliance.

IfcSharedSpatialElements: This scheme covers the definition of spatial elements that are shared among several IFC domain or application type models.

The Domain/Applications layer provides a set of modules tailored for specific AEC industry domains. Within the Domain/Applications layer the following schemes and classes are included:

IfcArchitectureDomain: This scheme defines basic objects concepts used in the Architectural CAD applications that have not been generalized.

IfcConstructionMgmtDomain: This scheme contains defined types and classes that capture concepts and data requirements for construction management processes.

IfcFacilitiesMgmtDomain: This scheme defines basic concepts in the facilities management domain.

IfcHVACDomain: This scheme defines basic object concepts required for interoperability between Building Service domain extensions and other domain extensions.

7.4.2 AECXML STANDARDS

aecXML is a new schema to establish a common data format to transfer specific information over the Internet free from human intervention. This information may be resources such as projects, documents, materials, parts, organizations, or activities such as proposals, design, estimating, scheduling, and construction (aecXML, 2003). aecXML was initially developed and introduced to the construction industries by Bentley Systems. The name “aecXML” derives from AEC and XML “eXtensible Markup Language”. XML, a term for a type of structured text data, is derived from the earlier SGML “Structured Generalised Markup Language”, which in turn derived from its well known sub-set HTML “HyperText Markup Language”.

aecXML is textual representation of data. The basic components in aecXML is the *element*, that is, a piece of text bounded by matching tags such as <BeginDate> and

</BeginDate>. Elements may contain other elements, “raw” text, or a mixture of the two. Consider the following example:

<Person>
<Name> Sami </Name>
<PhoneNumber> (919) 111-1111 </PhoneNumber>
</Person>

The Name element is delimited by the start-tag <Name> and the end-tag </Name>, and it contains only character data. The text between the start-tag and the corresponding end-tag, including the embedded tags, is called an *element*, and the structures between the tags are referred to as the *content*. The term *subelement* is also used to describe the relation between and element and it is component elements. Thus <Name>…</Name> is a *subelement* of <Person>…</person> in the example above.

Examples of aecXML elements are <BuildingComponent>, <Document>, <ConstructionData>, <Assembly>, <AssemblyCost> etc. The aecXML elements can be used across multiple disciplines. There are no predefined tags in aecXML; new tags may be defined at will.

7.4.3 THE COMPARISON

The developed taxonomy is conceptually related to the development concepts of the Industry Foundation Classes (IFC’s) and aecXML standards. However, because of their distinct target scope, the focus and detail of the two systems are different. The purpose of the IFC and aecXML standards is to enable data exchange, sharing, and interoperability within architecture, engineering, and construction (AEC) applications throughout the project lifecycle. As they are currently proposed, The IFC standards are designed to represent all graphic data involved in the AEC industries, while the aecXML system is designed for all non-graphic data.

The IFCs have a rich library of objects designed for recording Architecture, Engineering and Construction (AEC) information data. On the other hand, the IFCs don't provide the data structure that is needed for modeling construction operations. For example, the IFCs don't have clear criteria that describe the decomposition of objects into its basic components. Consider the following example; the *IfcBuildingElement* includes all elements that are primarily part of the construction of a building, such as walls, beams, etc. The wall is modeled in the *IfcWall class*, a subclass of *IfcBuildingElement*, however, there is no clear guidance on how to decompose the wall into its elements and record the decomposition information in the IFCs.

The developed taxonomy provides a clear guidance on how to decompose construction activities into their basic elements. The taxonomy provides three primary hierarchal levels that describe decomposition of any facility: product, assemblies and subassemblies, and components. For instance, a brick wall can be modeled as a subassembly and the bricks that make up the wall can be modeled at components level. Each component can have its own geometrical and physical representation based on its type.

Furthermore, the extent of the IFCs scope is much bigger and more complex than what is needed for the modeling construction operations alone. Other classification in addition to the IFCs needs to be developed to achieve the goal of modeling construction operations as described in the developed taxonomy. Thus, the taxonomy becomes remarkably important because it focuses on the classification structure of construction work at several levels of details, so that construction operations can be usefully modeled. On other hand, the IFCs doesn't breakdown the construction work into well defined operations (i.e. move, cut, etc.), but it provides the rich library of classes where the information can be defined and recorded.

To demonstrate how the taxonomy intersects or overlaps with the IFCs, we chose to partially map the proposed taxonomy to the IFC standards. The mapping process shows how the two systems intersect and point out the potential use of the taxonomy to enhance the current IFCs in order to adequately support modeling of construction operations. For example, there are two major classes in the IFC's that support the modeling of construction operations and processes, as they are presented in the developed taxonomy: *IfcProcess* and *IfcWorkTask*. Both classes are defined at the core layer. The *IfcProcess* class represents any general actions taking place in completing any architecture, engineering, or construction work. On the other hand, the *IfcWorkTask* class, a subtype of *IfcProcess*, can be used to represent processes that make up a construction operation. The *IfcWorkTask* class includes information such as work plans, work methods, and scheduling data. Again the IFCs only provide the class where work tasks can be defined, but the classes don't provide explicit guidance regarding the classification of construction operations, for example "CUT".

The *IfcProcess* class can be mapped to the operation level in developed taxonomy just as the *IfcWorkTask* class can be mapped to the process level. *IfcWorkTask* can represent a process at any level of detail, from the overall project level to very detailed tasks. For example, the project development phase, systems design, construction activities, and construction operations can all be represented as instances of *IfcWorkTask*. In addition, the *IfcRelNestsProcesses* class can be used to represent the relationships between a work task and its subtasks.

The *IfcRelProcessOperatesOn* class can be used to establish a relationship between processes (*IfcProcess*) and the products (*IfcObject*) upon which they operate. Construction operations such as, MOVE, CONNECT, etc. can be defined in this class.

Also, the *IfcResource* class can be used to represent the role that certain 'thing' plays on a construction project. The IFCs currently supports five different resources types: subcontractor, construction equipment, and construction material, crew, and product resources. A product resource is used in the case where a product that results from a work task is used as a resource in another process. The *IfcResouce* class can be mapped to the component level in the taxonomy.

The *IfcResource* class doesn't represent the 'thing' it self. Therefore, in situations where further information is needed about the 'thing' that is being modeled as a resource, the *IfcResource* class can be associated with other instances that represent those things, such as *IfcMaterialRes*. This is a key element to the development of the physically-based modeling approach where information about the physical properties of resources is needed to determine their physical behaviors.

The mapping approach of the developed taxonomy to the IFCs clearly shows the areas where the two systems overlap. As described above, at the conceptual level, both systems agree on the definition of things such as construction process, construction operations, and construction resources. However, the taxonomy provides a more explicit guidance on how to decompose a product into its basic elements, and on how to classify construction work into standard set of operations employing a common construction language.

Because of the focuses on inter-process interoperability, the IFC may not address as much specific detail information of various construction operations functionality as is needed to adequately support modeling of those operations. Therefore, the taxonomy can be looked upon as complementary efforts to extend the IFC objects in areas where the IFCs themselves are insufficient to support modeling of construction operations. Nonetheless, the taxonomy has the potential to provide a prototype that may eventually be adopted as an IFC extension that supports the modeling of construction operations.

On the other hand, the aecXML is a standardized means of communicating information in a business transaction, not a repository for holding it. aecXML can be used to agree on what certain 'things' mean, such as door or window, however aecXML won't model the thing. It complements the IFCs by providing a set of keywords and named data attributes, so that all users will employ the same naming logic and grouping, and software will be able to make use of the data without being interpreted by humans.

7.5 A SCALABLE CONCURRENT TAXONOMY: INTEGRATED PRODUCT AND PROCESS DEVELOPMENT

In order to address the issue of scalability, micro-modeling, and macro-modeling during the various design and construction phases, a concurrent structure that describes the design and construction phases based on their potential level(s) of interface with the proposed taxonometric structure is needed.

Typically, products that are produced by the AEC industry go through several distinct phases in their life span. Traditionally, those phases are carried out in a linear fashion that makes it difficult to integrate the modeling system at the early stages of the design process. Therefore a different design approach that focuses on the realization of the product is needed. Unlike traditional design approaches, the developed concurrent structure describes the following design and construction phases: feasibility study, conceptual design, preliminary design, detailed design, construction planning, construction operations, and operation and support. The developed concurrent structure creates a hierarchical level of interactivity between the various design and construction phases. Also, it makes the integration between the various design phases and the taxonometric structure more feasible.

The concurrent structure distinguishes two categories of design and construction phases: product-oriented phases and process-oriented phases. The product-oriented category includes the feasibility study, conceptual design, and preliminary design. Where the process-oriented category includes the construction planning, construction operations, and operation and support phases. The detailed design phase falls under both categories and bridge the gap between the product-oriented phases and the process-oriented phases.

Similarly, the concurrent structure implements the same classification methodology that described in the taxonometric structure. The product, assembly, and component levels of the hierarchal taxonomy are categorized as product-oriented levels. While the operation, process, physics and controls levels are classified as process-oriented levels.

The product-oriented and process-oriented categories create a common ground between the design and construction phases and the taxonometric structure. The next step is to establish the interfaces between each of the design phases and various levels within the taxonometric structure. As shown in Figure 7.5, the design phases and the taxonometric levels from the product-oriented category are linked together. For instance the preliminary design phase is linked to the assembly and component levels. In the same way, the interface between the phases and levels in the process-oriented category were established.

The established links between the design phases and the taxonometric levels defines the complexity and the level of detail for the construction models that interfaces with the product or process design phases. The taxonometric structure supports this philosophy because it is structured to model construction operations at various levels of detail including the macro-level and the micro-level.

For example, at the operation level during the process design of a wall construction, the construction process designer, for constructability reasons, determined to use drywall on steel studs rather than masonry construction, as defined by the product designer. The information generated from the operation level offers recommendation regarding the desired wall components including materials and tools. The wall components are defined at the component level. Therefore, information collected from the component and assembly level may have significant input into the product design at the preliminary design phase.

Macro-Modeling refers to higher level decision making, while micro-modeling refers to the detailed level of decision making. For instance, the process level can be classified as a micro-modeling level when compared to the operation level. The process level returns all the processes needed to complete a construction operation. The same concept exists in the design and construction phases as well. The detailed designed phase is considered a micro-design phase when compared to the preliminary design phase; however, it is considered a macro design phase when compared to the construction planning phase.

To illustrate how the proposed taxonometric structure can be usefully utilized at various design phases let us consider a steel structure example. At the conceptual design phase, product designers are only interested in the overall project and its major assemblies. It is considered a tedious practice to present the designer with detail from construction operation and process levels to consider during the conceptual design phase. Thus, a higher-level model (macro-model) can be presented to the product designer from the assembly level to show the configuration of the steel structure assembly. Afterward, during the preliminary design phase the designer can be presented with more detailed models, which includes models from the assembly and components levels.

In summary, the proposed concurrent structure, shown in Figure 7.5, forms the basis where the issue of scalability can be implemented. Also a new classification was developed to usefully facilitate the use of taxonometric structure during the various design stages.

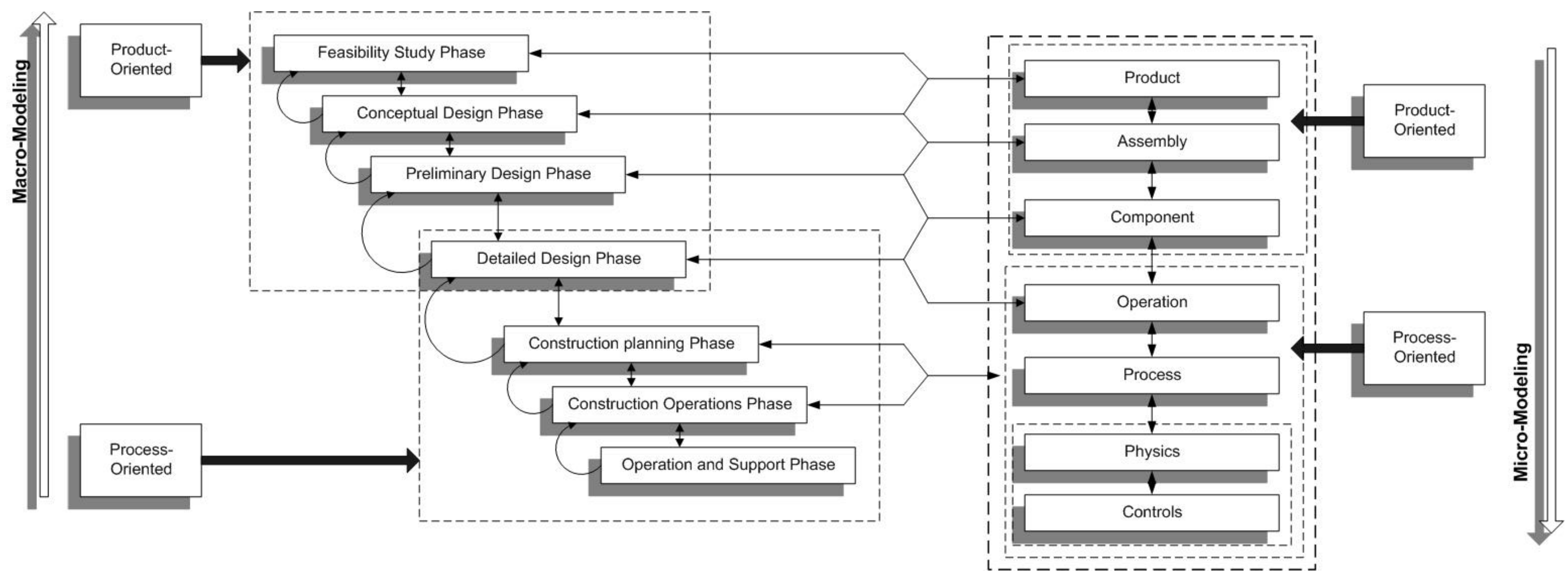


Figure 7.5: Areas of potential concurrency between the design process and taxonometric structure.

7.6 THE DEVELOPED TAXONOMY AND THE CRADLE-TO-CRADLE APPROACH

The developed construction modeling system was structured in a way to describe and capture construction operations in which man power, tools, machines, and energy transform material into a constructed product. This section investigates the adaptability of the developed taxonomy by increasing the scope of accountability to include cradle-to-cradle responsibility.

7.6.1 CRADLE-TO-GRAVE APPROACH

As depicted in Figure 7.6, the cradle-to-grave term is used to describe products and facilities that are designed in a linear, one-way cradle-to-grave approach. Cradle-to-grave designs dominate modern manufacturing and constructed facilities. Based on the cradle-to-grave approach, resources used in the design and construction of facilities are eventually disposed in a 'grave' of some kind at the end of their useful 'life', usually a landfill.

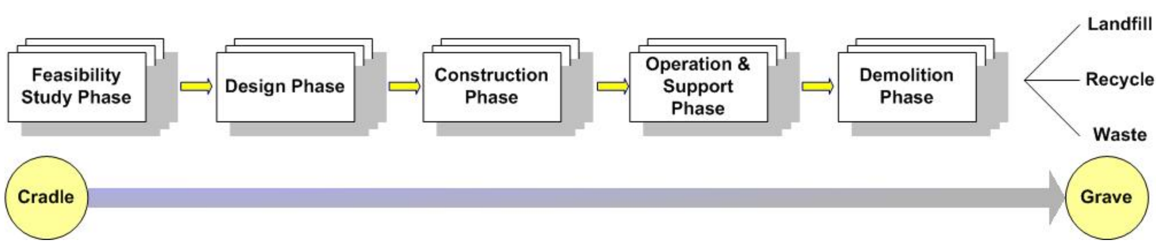


Figure 7.6: Cradle-to-grave facilities life cycle.

7.6.2 CRADLE-TO-CRADLE APPROACH

Alternatively, as shown in Figure 7.7, concerns about the environment have spurred interest in cradle-to-cradle approach, the practice of designing products and facilities with consideration of their entire 'life', from initial conceptual design, through normal facility use, to eventually the recycling of the facility components into something new. Furthermore, the cradle-to-cradle design paradigm focuses on products that can be broken down and perpetually circulated in closed loops, made and remade as the same product or other products.

One of the examples that implemented the cradle-to-cradle approach in design and construction is Ford's River Rouge new plant project designed by architect William McDonough (McDonough and Braungart, 2002). Architect William McDonough is well known for his green architecture designs, which utilize the cradle-to-cradle approach. For example, one of the features of the plant is the roof, a full 10.4 acres of sedum, whose unique absorption properties provides natural storm water management. The use of sedum provided natural insulation and eliminated the need for roof painting.

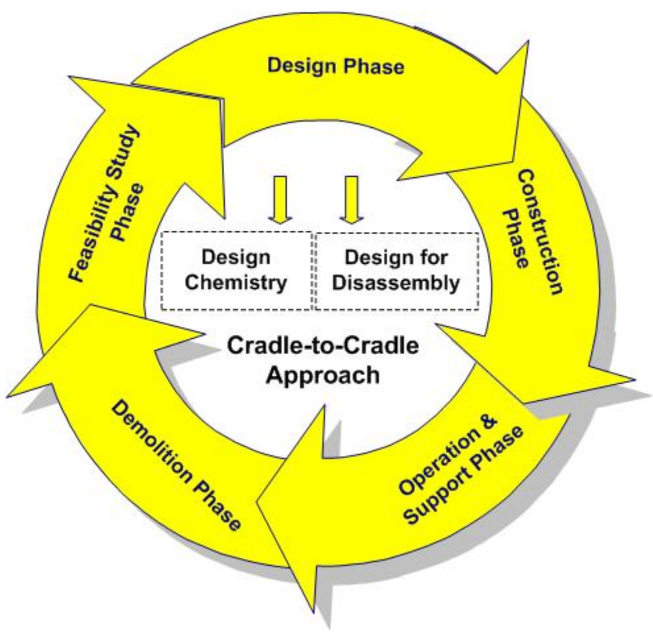


Figure 7.7: Cradle-to-cradle facilities life cycle.

7.6.3 ELEMENTS OF CRADLE-TO-CRADLE APPROACH

Design chemistry and design for disassembly are two of the major elements of cradle-to-cradle approach. Both elements might affect the modeling of construction operations in different ways. The design chemistry incorporates scientific and ecological knowledge into products and processes design, while the design for disassembly focuses on the design of products that can be dismantled for easier maintenance, repair, recovery, and reuse of components and materials.

7.6.3.1 Design Chemistry

The design chemistry concentrates on the evaluation of the materials chemicals and production processes based on human health and environmental relevance criteria. The evaluation of materials chemicals plays a major role in determining the selection criteria of construction components. As depicted in Figure 7.8, ideally, components and materials are selected during the design phases based on the design chemistry principles. Once a component passes the materials chemicals assessment then it will be added to the cradle-to-cradle list of material. Otherwise recommendations will be made to develop or select a new component that meets the cradle-to-cradle material requirements.

The cradle-to-cradle material list may include only those materials that follow the principles of design chemistry. Subsequently, those components and their materials will be identified in the component material library in order to be used in the cradle-to-cradle modeling of construction operations. The component material library can be part of the component level in the developed taxonomy.

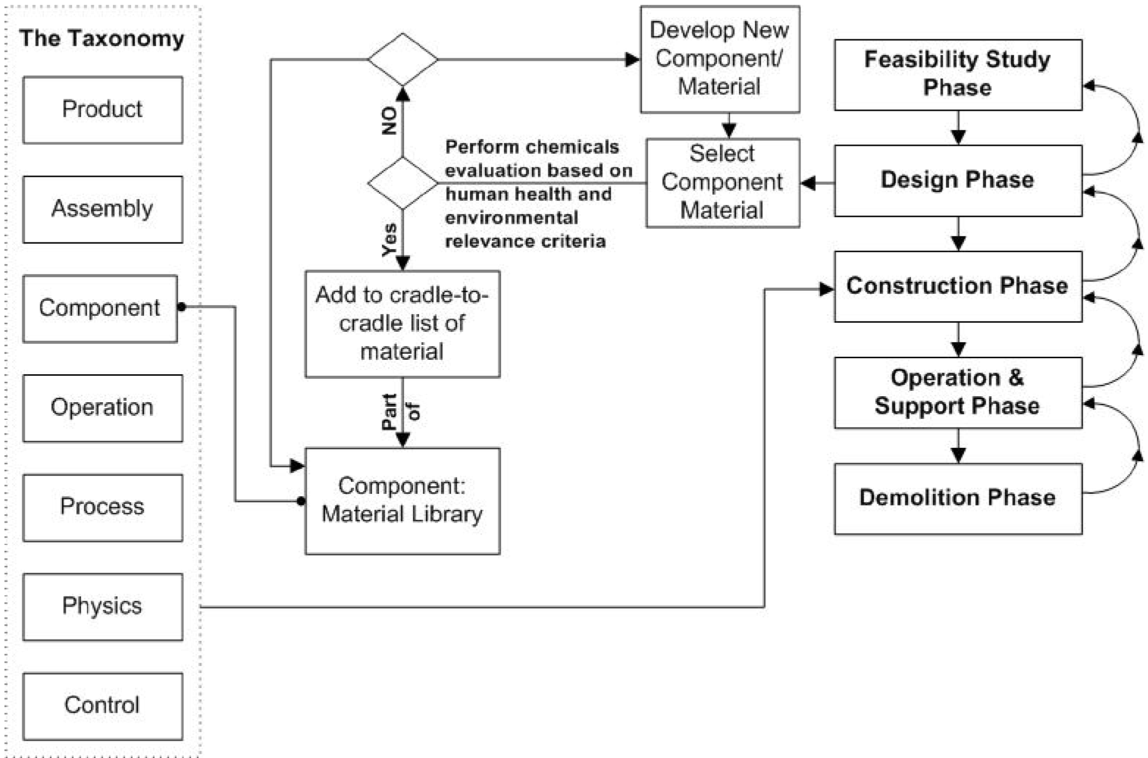


Figure 7.8: The evaluation of materials chemicals.

Material selection criterion can become one of the design constraints, where the highest priority of material selection is given to the cradle-to-cradle material during the modeling of construction operations.

The second aspect of design chemistry that affects the modeling of construction operations is to assess the burdens of production processes on human health and the environment. The assessment can be done by evaluating the energy, materials, and releases to the environment resulted from each production or construction process. The developed taxonomy includes two levels that are used to describe the way in which man power, tools, machines, and energy transform material into a constructed product, the operation level and the process level.

As depicted in Figure 7.9, a CUT operation is used to describe the processes and resources involved in cutting a steel element. Resources are defined at the component level and include material (steel members), tools (circular saw), manpower (labor), energy, etc. While processes such as, reach, touch, grasp, etc. are defined at the process level. Each component of the 'cut steel element' operation, whether it is a resource or a process, can be evaluated and analyzed according to the principles of design chemistry. For example, instead of using flaming cutting machine, circular saw might be selected as cutting to minimize the releases to the environment. The outcome of the evaluation can be used to identify environmental improvement opportunities.

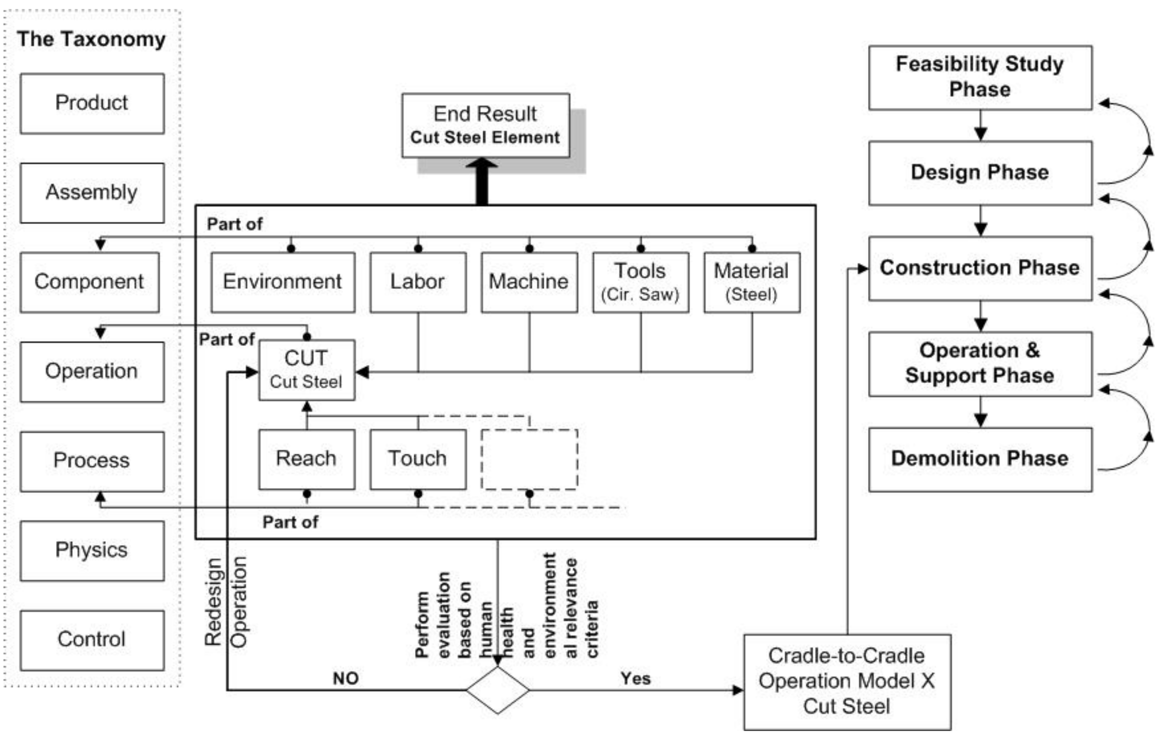


Figure 7.9: The evaluation of production processes.

Once the operation 'cut steel member' meets the cradle-to-cradle production processes criteria then it may be modeled and defined as a cradle-to-cradle operation. Otherwise, the ‘cut steel member’ operation will go through several redesign cycles until satisfactory results are achieved.

7.6.3.2 Design for disassembly

Another aspect related to the cradle-to-cradle approach is the disassemblability of constructed facilities. According to cradle-to-cradle approach, after a facility has completed its useful life, it must be disassembled then, reused or recycled.

Facilities that are designed for disassembly can be quickly and easily broken down so that the components can be repaired, reused, or recycled. Therefore, designer and builders should evaluate the ease of disassembly operations during the early design stages. The evaluation can be performed in two ways: one by studying the design drawing and the technical specifications or by building a prototype to study the disassembly operations. Prototypes can either be physical or virtual. Physical prototypes are expensive and time consuming to build and modify, while virtual prototypes often can be generated and modified quickly to test new concepts. Thus, disassemblability can be evaluated by performing disassembly operations on virtual prototypes utilizing the developed construction modeling system.

In order to evaluate disassemblability, a disassembly process model is needed. The disassembly process model describes information regarding disassembly operations sequence, component removal sequence, and tools information etc. Information needs to be structured and stored in a useful way to allow later evaluation of disassemblability; simulation of the disassembly processes; and optimization of the disassembly processes.

Useful information related to the disassembly processes can be captured by the developed modeling system at several levels of detail. Figure 7.10 shows the disassembly sequence of components, operations, processes, and the components needed to complete the disassembly of column 6A.

Three construction operations are needed: PLAN, CUT, and MOVE. PLAN the disassembly work for column 6A, then CUT (unfasten) nuts 6A-1, 6A-2, 6A-3, and 6A-4, and finally MOVE the column with the aid of mobile crane. These operations are defined and captured at the operation level. The detailed processes (e.g., grasp and unfasten) of the CUT operation are captured at the process level. The component and resources are captured at the component level (e.g., a mobile crane or steel column 6A).

In summary, the developed taxonomy and its modeling system can be expanded to increase the scope of accountability to include cradle-to-cradle responsibility. Modeling the disassembly processes of products is a subject with considerable potential for a future research that expands on the developed taxonomy.

7.7 SYNOPSIS

In Chapter Seven, a common taxonomy for modeling construction operations is developed. First, the taxonometric hierarchy consists of seven levels of classification: product, assemblies and subassemblies, components, operations, processes, physics, and control.

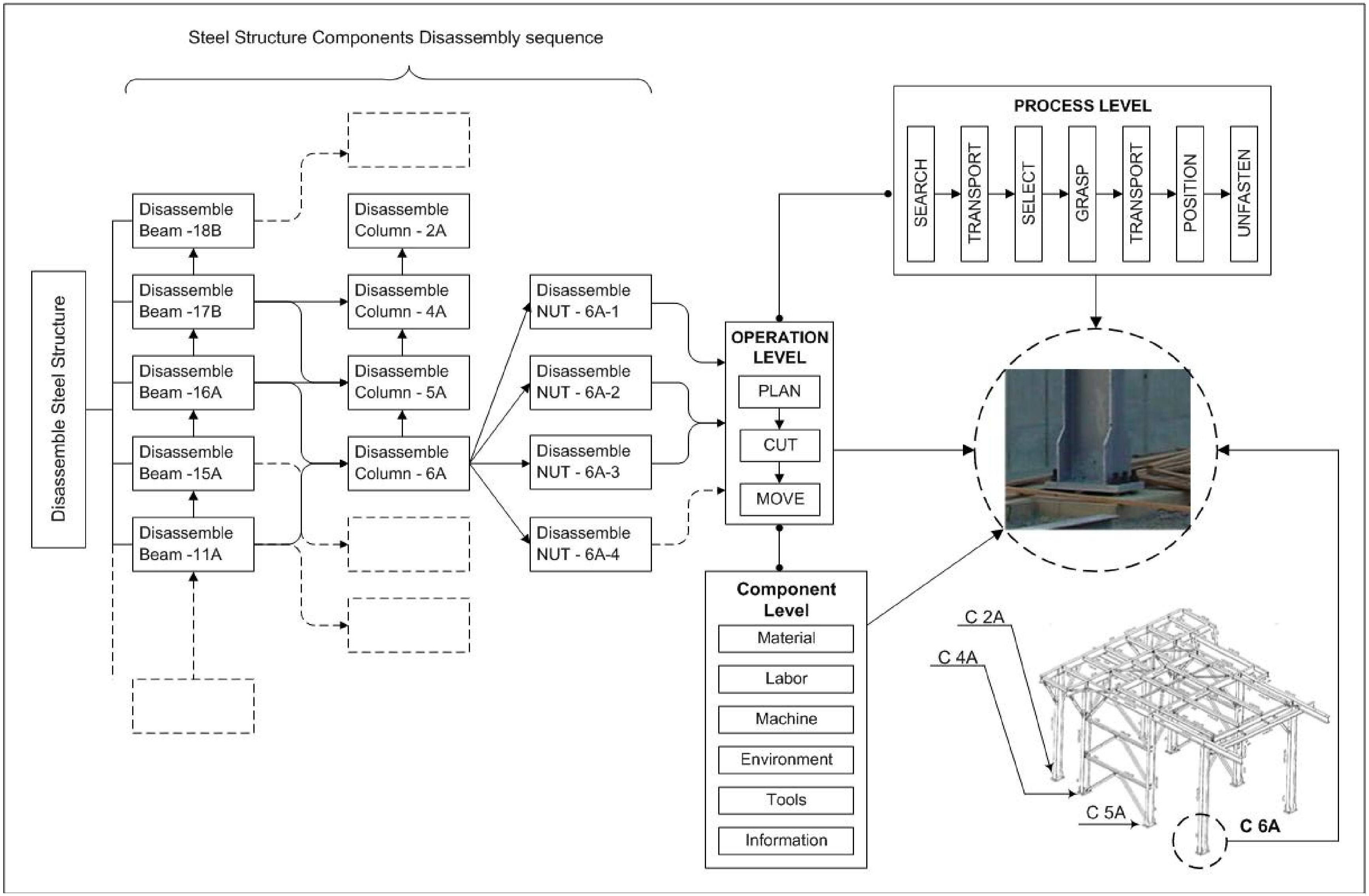


Figure 7.10: Disassembly process of steel structure

The seven hierarchical levels are established by examining the ways that construction field operations are being carried out. Second, six major blocks of construction knowledge are identified and information about the interaction processes that is required to model construction operations in a logical way are described. Third, schemes for modeling information in the construction domain such as aecXML and IFC's are presented. Then the developed taxonomy is partially mapped to the IFC standards to identify where both systems intersect or overlap and their advantages and limitations. Fourth, areas of potential concurrency between the design process and the developed taxonometric structure are presented.

Also, a new concurrent classification structure is developed to usefully facilitate the use of such a structure during the various stages of design. The new concurrent classification structure distinguishes between two categories of design and construction phases: product-oriented phases and process-oriented phases. Finally, this chapter investigates the adaptability of the developed modeling system by increasing the scope of accountability to include cradle-to-cradle responsibility. Design chemistry and design for disassembly are discussed and an example for the disassembly of a steel structure is presented.

CHAPTER EIGHT: EXAMPLES AND VALIDATION

8.1 INTRODUCTION

Current practices have isolated product development (facility design) from the processes (construction operations and methods) that lead to the physical realization of the product. It is clear that there are two distinct paradigms; one engineering, one construction. “Let the field figure that out,” say the designers. “We can build it from anything,” say the constructors. These paradigms have gone unchallenged for so long that they became self-perpetuating. As designers did less, the tasks required of constructors increased. While understanding that there are various reasons that have caused this situation to occur, the reasoning will most likely need to be altered to allow the designers the time to completely assist the constructor.

Design engineers tend to focus only on obtaining information that’s necessary to complete the design and, in the process, not necessarily giving much thought on how this information affects construction in the field. While it is necessary for the design to be completed in a timely manner, this is only a portion of the over all picture. There is a whole other world out on a construction site and when engineers haven't had the opportunity to go out and see first hand how the designs they produce are constructed in the field, it's difficult to recognize the areas of improvement and gain an understanding of how to improve their design to enhance construction execution.

One promising approach to gain this understanding is to apply the developed framework that establishes closer working relationships between designers and constructors from the very beginning of project inception. The developed framework in this dissertation supports this thought; with the goal to learn across the complete project by using a common modeling language.

8.2 IN-FIELD EVALUATION

The main purpose of the in-field evaluation is to validate the suitability of the developed framework and its construction modeling system (the common taxonomy). The in-field evaluation engaged interdisciplinary teams that are directly or indirectly involved in power plants design and construction. The interdisciplinary teams included personnel from the management, estimating, planning and scheduling, engineering and drafting, procurement, construction, and finally startup and commissioning groups.

From the available research methodologies, action research methodology was chosen for the evaluation and validation of the developed modeling system. Action research is considered here as a systematic study of attempts to improve the developed construction modeling system in this thesis by groups of participants, by means of their own practical actions, and by means of their own reflection upon the effects of those actions.

The purpose of this in-field evaluation is to address and answer the following basic questions:

1. Is the developed framework suitable for modeling construction operations?

2. What are the strengths and shortfalls of the developed framework?

8.3 EXAMPLE SELECTIONS AND THE CONSTRUCTION OF POWER PLANTS

8.3.1 BACKGROUND

The construction of power plant is a three-legged stool consisting of design, procurement, and construction. In the past two decades, significant improvements and reductions have been made in the overall project schedule by continuously applying advanced tools and methods to the design process. Also, similar reductions have been achieved in the procurement schedules as a result of re-engineering the procurement process. This leaves construction as the logical remaining place to look for additional significant schedule reduction.

Some project schedule reduction has already been achieved by overlapping design activities and procurement activities with early construction activities as shown in Figure 8.1. Further significant project schedule reductions will come only from planning to initiate multiple parallel construction activity paths. These multiple parallel construction paths can be realized by use of the following techniques: prefabrication, preassembly, and modularization.

The construction power industry continues to strive for the answers to the cost reduction and schedule reduction challenges. This has been especially true in the past few years. Techniques such as prefabrication, preassembly, modularization have been introduced and implemented whenever and wherever possible. However, due to contractual obligation, tight construction schedule, or limited available resources, these techniques were not analyzed or improved upon prior to actual construction. This issue was discussed with constructors from four different trades (concrete, steel, mechanical, and electrical). They all agreed that there is a need for improvement, but there were neither time nor resources available to improve upon their knowledge of construction techniques. Most important, there is no common construction language that can be used to capture and analyze construction operations. Some of the constructors were creative and implemented new and uncomplicated concepts to improve the quality and constructability of their trade. However, the majority of constructors do things the way “they have been taught”.

8.3.2 EXAMPLE SELECTION

Figure 8.2 provides an overview of the steel structure example chosen to validate the applicability of the developed taxonomy in modeling construction operations. The erection of steel structures is an integral part of the construction of the Calhoun power plant in Calhoun, Alabama. The Calhoun project incorporated four major, trades (concrete, steel, mechanical piping and electrical) and represented different levels of complexity.

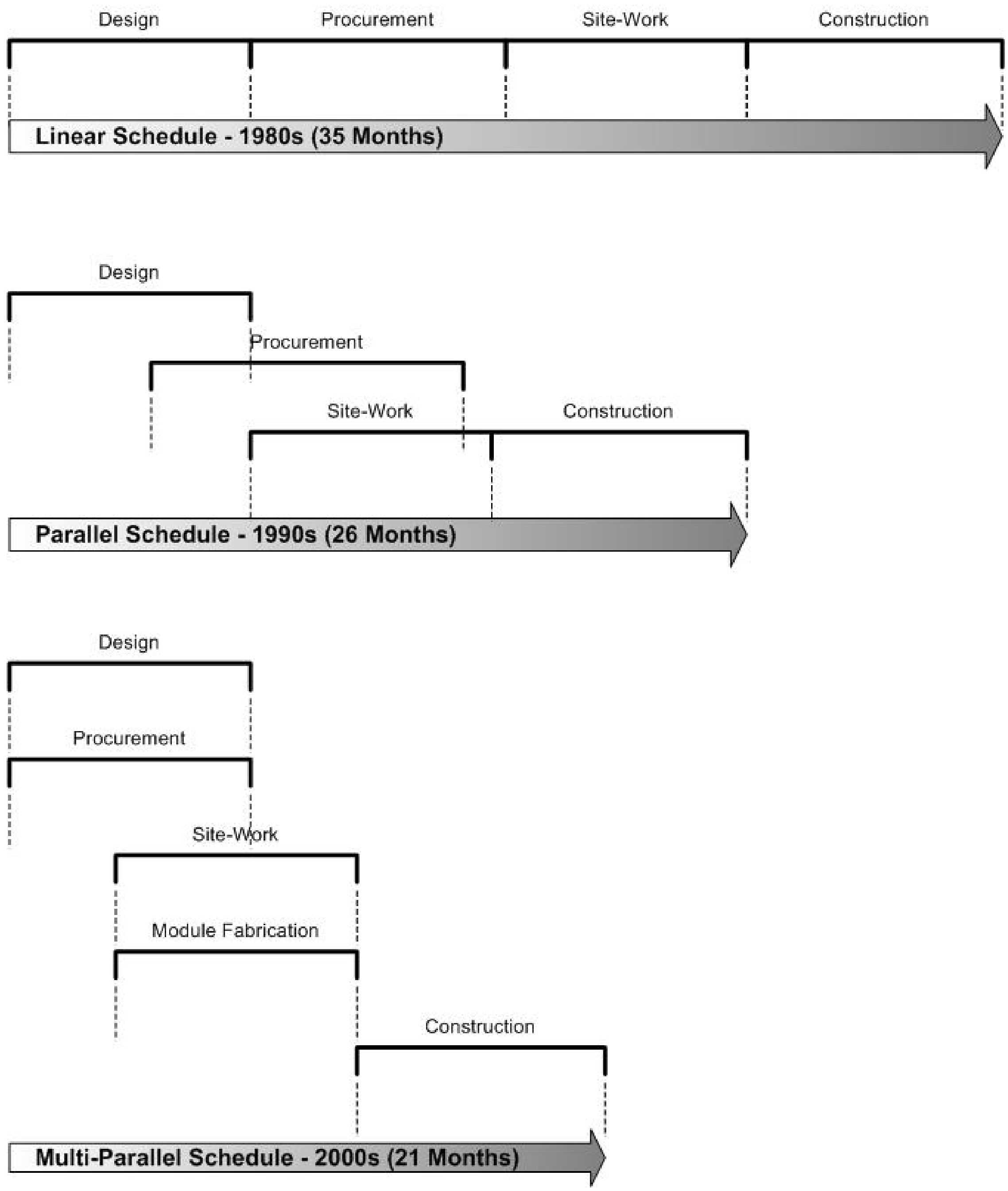


Figure 8.1: Comparison of linear, parallel, and multi-parallel scheduling for 7FA simple cycle power plant (Black and Veatch, 2000).

Furthermore, this project is unique in several ways. First, this project was designed and planned based on inherited knowledge from a previous successful project "Doswell Power Plant Project". Lessons learnt from the Doswell project were recorded, analyzed and improved upon by the design and the construction teams. These lessons under went further examination before they were incorporated in the Calhoun project. Second, the same teams that designed, procured, and constructed the Doswell project were assigned to the Calhoun project. Third, both projects use similar power generation technology, "Simple-Cycle generation technology". The Doswell project consisted of one simple-cycle machine; while the Calhoun project is more complex with four simple-cycle machines. Two of the four simple-cycle machines will eventually be converted to a "Combined-Cycle Power Plant".

We chose this very specific, yet complex example of construction operations as test bed for the development and validation of the developed construction modeling system for several reasons: First, the assembly problem is very narrow and well known. Therefore, a limited and reusable number of modeling objects can be easily developed. Secondly, our goal is to validate and demonstrate by example the potential use of the developed taxonomy to model construction operations. Thus, a very intuitive example with a short learning phase is required.

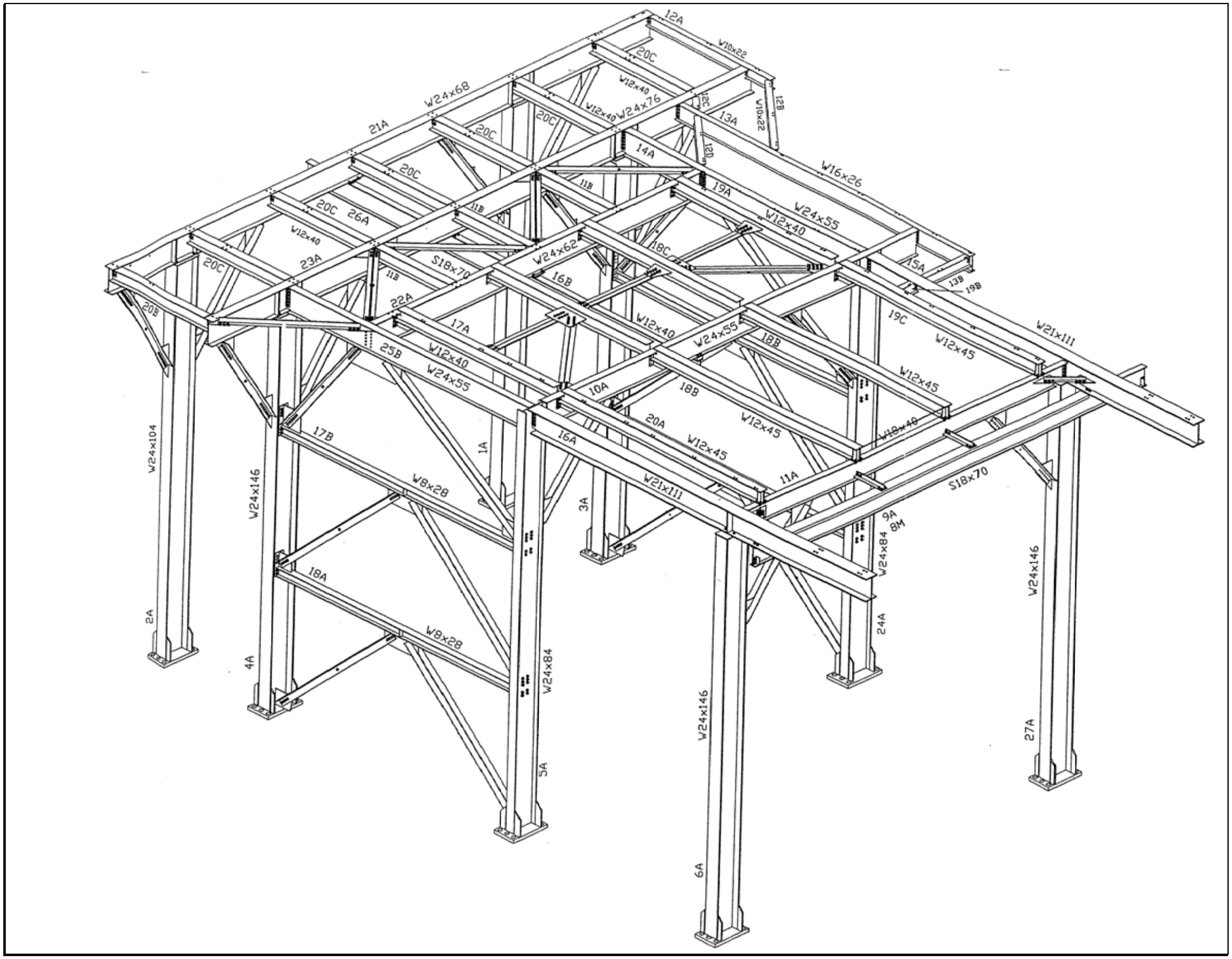


Figure 8.2: 3D model of the steel structure assembly from the Calhoun project, showing size designations for columns and beams and the identification number of each part.

8.4 VALIDATION OF THE TAXONOMY

This section describes by example the fabrication, assembly, and erection of the steel structure shown in Figure 8.2 and 8.4. The main goal of this example is to validate the capabilities of the developed taxonomy to model construction operations. Furthermore, the flow charts and the operations models developed for this example describe the fabrication and erection operations as they were recorded at either the fabrication shop or the construction site. Therefore, those models might not represent best construction practices and excellence. The goal is map those operations to the developed taxonomy and record them so they can be further analyzed and potentially improved.

8.4.1 THE PRODUCT

The product is a power plant project (see Figure 8.1). This particular project consists of four identical simple cycle machines that are currently under construction in Calhoun, Alabama.

Figure 8.3: The power plant project.

8.4.2 THE ASSEMBLY

Steel structures are one of the major assemblies in power plant projects. Steel structures are used as support structures where piping, mechanical and electrical equipment set. The filter house steel structure assembly is shown in Figure 8.4.

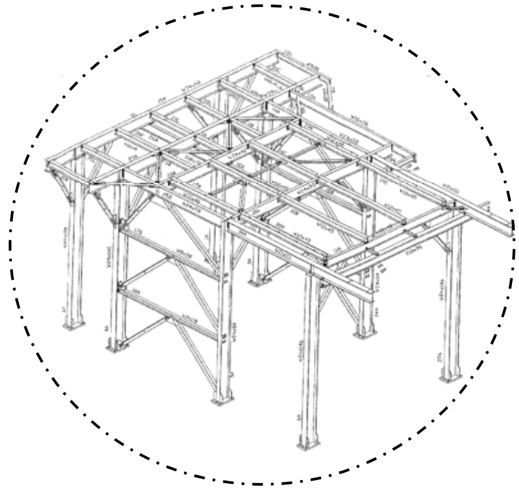


Figure 8.4: The steel structure assembly.

8.4.3 THE COMPONENT

There are six major components that lead the realization of a construction assembly; material, manpower, machine, environment, tools, and information. This section describes the product breakdown of the steel structure assembly, the list of needed machines and tools, and information regarding the common fastening techniques for steel assemblies.

8.4.3.1 Product Breakdown of the steel structure assembly

Table 8.1 lists the steel structure assembly material, parts and components. As shown on Figure 8.2, each component is identified with a part identification number (ID) marked on each part which corresponds to the Part ID's shown in Table 8.1.

Table 8.1: The steel structure assembly components and parts.

Product Breakdown			
Part ID	**Part Type**	**Part Specifications**	**Quantities**
1A	Column	W24x104	1
2A	Column	W24x104	1
3A	Column	W24x146	1
4A	Column	W24x146	1
5A	Column	W24x84	1
6A	Column	W24x146	1
7A	Angle	L6x6x3/8	6
7B	Angle	L6x6x3/8	6
7C	Angle	L6x6x3/8	8
7D	Angle	L6x6x3/8	8
7E	Angle	L6x6x3/8	4
7F	Spacer	PL1/2x4x0-4	10
7H	Angle	L3 1/2x3 1/2x1/4	2
7G	Angle	L3 1/2x3 1/2x1/4	2
7J	Spacer	PL1/2x6x0-6	26
8A	Angle	L6x6x3/8	4
8B	Angle	L6x6x3/8	4
8D	Angle	L4x4x1/4	4
8E	Angle	L4x4x1/4	4
8F	Angle	L4x4x1/4	4
8H	Angle	L4x4x1/4	2
8J	Angle	L3 1/2x3 1/2x1/4	4
8M	Angle	L4x4x1/4	6
9A	Beam	S18x70	1
10A	Beam	W24x55	1
11A	Beam	W18x40	1
11B	Beam	W12x40	3
12A	Beam	W10x22	1
12B	Beam	W10x22	1
12C	Beam	W10x22	1
12D	Beam	W10x22	1
13A	Beam	W16x26	1
13B	Beam	W10x22	1
14A	Beam	W24x55	1
15A	Beam	W21x111	1
16A	Beam	W21x111	1
16B	Beam	W12x40	1
17A	Beam	W12x40	1
17B	Beam	W8x28	2
18A	Beam	W8x28	2
18B	Beam	W12x45	2
18C	Beam	W12x40	1

Product Breakdown			
Part ID	**Part Type**	**Part Specifications**	**Quantities**
19A	Beam	W12x40	1
19B	Beam	W10x22	1
19C	Beam	W12x45	1
20A	Beam	W12x45	1
20B	Beam	W12x40	1
20C	Beam	W12x40	6
21A	Beam	W24x68	1
22A	Beam	W24x62	1
23A	Beam	W24x76	1
24A	Column	W24x84	1
25B	Beam	W24x55	1
25C	Angle	L6x6x1/2	4
25D	Angle	L6x6x1/2	4
25E	Angle	L4x4x3/8	8
26A	Beam	S18x70	1
27A	Column	W24x146	1
	Bolts	1"x3 1/4"	68
	Bolts	1"x3"	370
	Bolts	1"x2 3/4"	251
	Bolts	1"x2 1/2"	150
	Nuts	1"	839
	Washer	1"	1660
	Bolts	3/4"x2 3/4"	10
	Bolts	3/4"x2 1/2"	10
	Nuts	3/4"	20
	Washer	3/4"	40

8.4.3.2 Tools and Machines

Once the fabrication drawings are completed and all the steel components involved in the erection have been detailed and identified, the tools and machines required to carry out the work can be defined. This section classifies two categories of tools and machines based on the location and type of work; shop fabrication tools and machines, and on-site erection tools and machines.

Shop fabrication tools and machines

The production lines in fabrication shops are usually organized in such a way that the material will pass through a one way system from receipt to final dispatch of material. Most fabrication shops are equipped with overhead traveling cranes or mechanized conveyer systems. Other tools and equipment may include:

- Crane equipped with chains and hooks, or cranes on conveyors with magnetic lifting devices.
- Measuring and marking tools.
- Cutting machines: circular saw, band saw, motor operated hacksaw, flame cutting, and laser cutting.
- Drilling machines, for example radial drilling machine.
- Surface machining and paint spraying machines and paint brushes.

On-site erection tools and machines

Cranes are considered the major piece of equipment for steel erection. Hoisting equipment of suitable capacity need to be available for any preassemblies, which must be lifted. The part that requires the greatest lifting capacity and the site conditions determines the minimum crane capacity to be used. Other tools and equipment that are required for on-site erection work may include:

- Cranes of various types.
- Bolting equipment, such as spanners, ratchet spanners, torque wrenches, etc.
- Welding equipment.
- Electric generators.

- Hydraulic Jacks.
- Measuring equipment such as levels, and laser equipment.
- Handling tools.
- Air compressors.
- Transport equipment
- Miscellaneous equipment such as pulleys, spreader beams, etc.
- Wire ropes, hoisting slings, shackles, etc.
- Paint spraying machines and paint brushes.

8.4.3.3 Manpower

Manpower can be determined in terms of personnel required to complete the erection of the structure.

8.4.3.4 Environment

The shop fabrication and the construction site are the two major environments that control the fabrication and erection of steel assemblies. The fabrication shop can be organized as a production line where most operations can be executed in controlled and standardized fashion. On the other hand, work performed at the construction site may be slowed down by adverse weather.

8.4.3.5 Information

Part of the information needed to complete the erection operation is the fastening techniques for steel structures. Steel elements can be joined together with any of three fastening techniques: rivets, bolts, or welds. Rivets were the major form of joining steel members before bolts came into wide use. Currently, the most common technique is bolting; it is quick and easy for field connection. On the other hand, welding is very expensive and rarely used on-site. The fastening techniques and their features are explained in Table 8.2.

Table 8.2: The common steel fastening techniques.

Fastening Technique	**Description**	**Features**
Rivets	Rivets are like round head screws with no threads, that are heated and inserted in the hole. With rivets, adjoining steel members are joined with a common hole. The end without a head is hammered flat, until the rivet is permanently attached to the hole.	It has been almost entirely replaced by bolting and welding. Labor-intensive.
Bolts	The most common method of joining members in a steel frame is with bolts, using smaller steel angles as transitional elements.	Quick and easy access. Can be accomplished under conditions of adverse weather. Recommended to be used in the field for assembly. Cost effective
Welding	The process of melting two steel elements together to form a monolithic form.	Recommended to be used in the fabricator’s shop. Relatively expensive when used in the field. Can’t be accomplished where difficult physical accessibility exists.

8.4.4 OPERATION

Figure 8.5 describes the general nature and the sequence of work that takes place at the design office, the fabrication shop, and the construction site. Typically, the engineering office issues the engineering drawings and technical specifications of the steel structure to the fabricator to commence fabrication. Then the fabricator prepares detailed fabrication drawings and erection sequences. The fabricator role is to transfer 'raw' material into finished products that can be easily assembled on-site. Also, the fabricator preassembles and assembles steel parts and components to reduce the amount of work to be done on-site.

The fabrication and delivery schedule is coordinated with the erection schedule and the capacity of the site erection team. The site erection team coordinates and handles the unloading of the fabricated elements. Then the erection starts as soon as the foundations and the anchor bolts are checked. The next two sections will provide further details regarding the operations needed for the fabrication and erection of the steel structure assembly as they occur either at the fabrication shop or the construction site.

8.4.4.1 The fabrication shop operations

As depicted in Figure 8.6, the basic flow of fabrication activities at the shop can be visualized as a tunnel for the main flow of major operations.

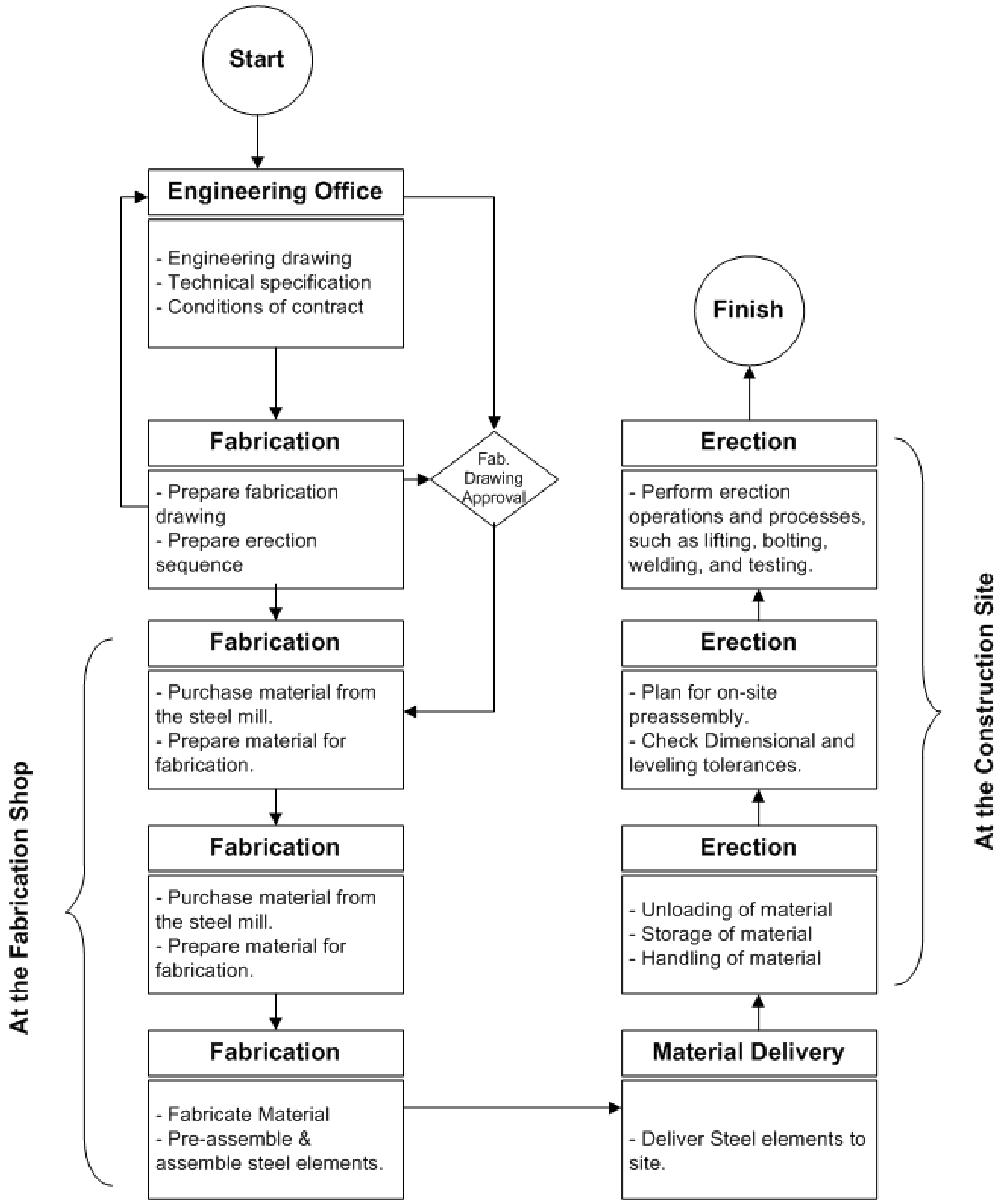
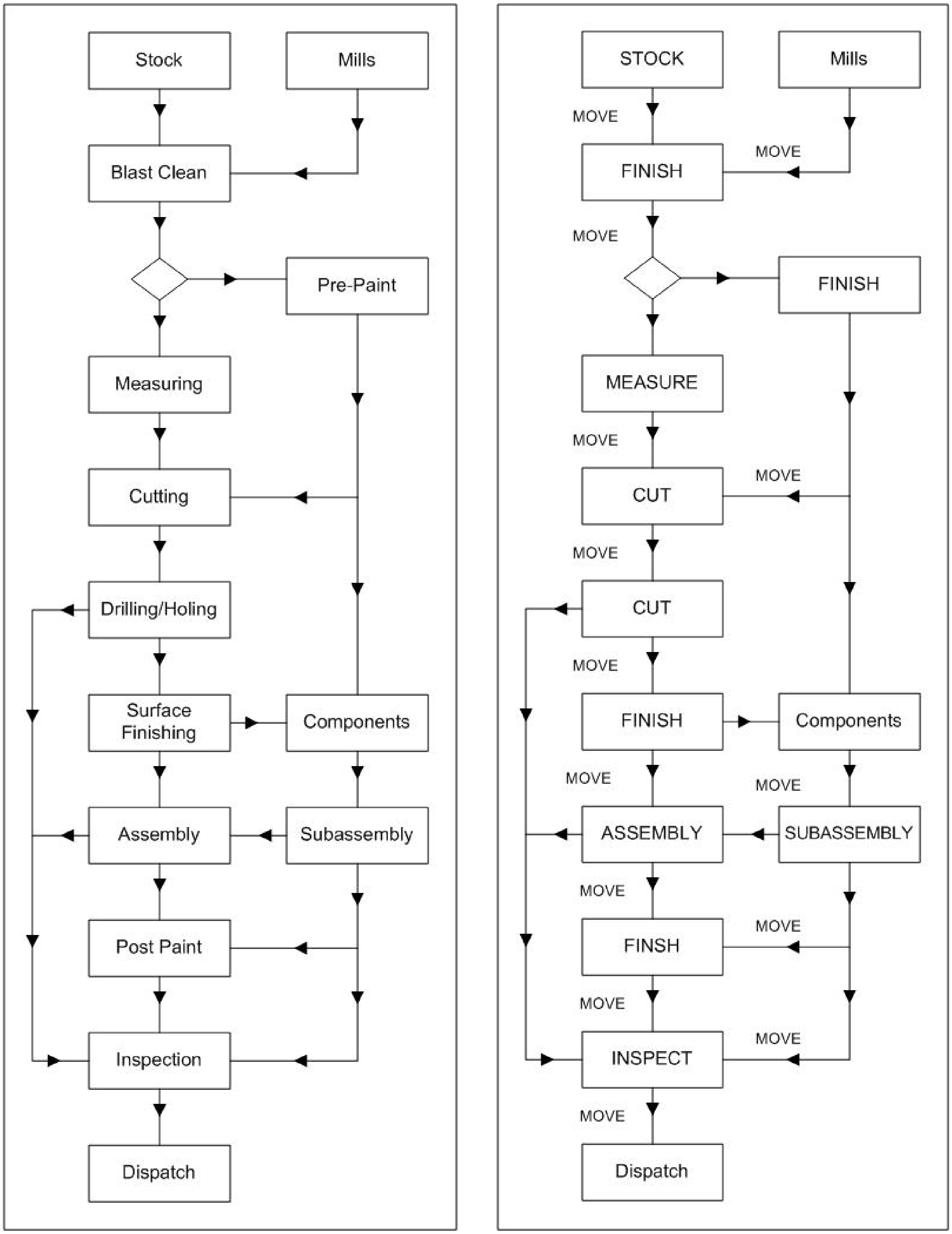


Figure 8.5: The general nature and sequence of steel work.



FAB shop flow. Taxonomy based flow.

Figure 8.6: The process flow map of major operations at the fabrication shop and their representations according to the taxonomy.

The left side of Figure 8.6 shows the fabrication operations and their relationships as they occur at the fabrication shop while the right side shows the representations of those operations according to the developed taxonomy. For example, the blast cleaning, pre-paint, and post paint process are represented by the FINISH operation, and the drilling cutting processes are represented by the CUT operation.

At the fabrication shop, a number of operations are performed in a linear way, such as blast clean, measuring, cutting, drilling, etc. while operations such as pre-paint, inspection, and assembly are performed in parallel. Figure 8.7 shows the linear operations on the X-axis and the parallel and multi parallel operations on the Y-axis.

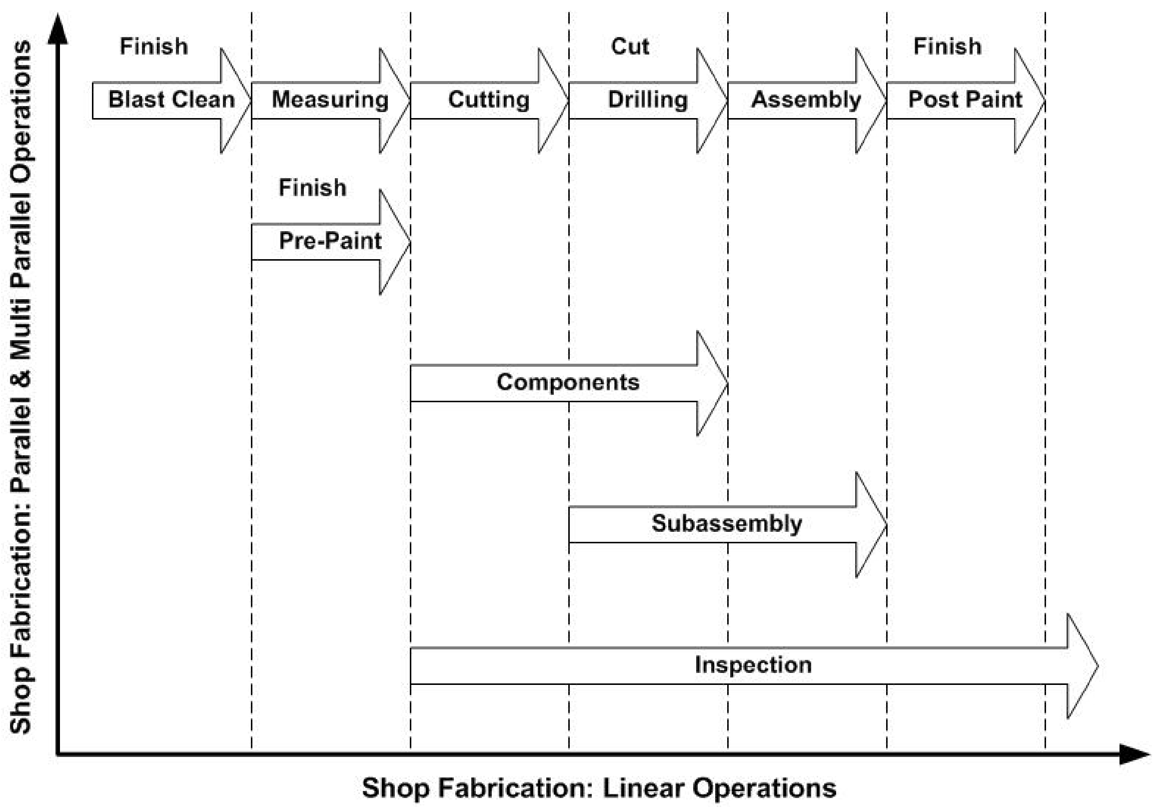


Figure 8.7: Linear, parallel and multi parallel shop processes.

Table 8.3 provides a list of the major steel shop fabrication operations, their descriptions, the needed equipment and tools, and their representation according to the taxonomy.

Table 8.3: Description, equipment and tools, and taxonomy representation of shop operations.

Shop Operation	**Description**	**Equipments/Tools**	**Taxonomy/Operation**
Material Handling	Unload the material from the transport equipment and stock it in a way that it can be easily identified and moved.	Crane equipped with chains and hooks. Or cranes on conveyors with magnetic lifting devices.	MOVE
Blast cleaning	Pass the material through a blast cleaning cabinet to remove any surface rust.	Blast cleaning cabinet.	FINISH
Measuring and Marking	Measure and mark the steel for cutting and for center popping where holes were to be drilled.	Measuring and marking tools	MEASURE
Cutting / Sawing	Transfer the material to the sawing station for cutting to length. The steel sections are placed on automatic sawing lines, equipped with mechanized longitudinal and transverse conveyors and measuring devices.	Circular saw; band saw; motor operated hacksaw; flame cutting; laser cutting	CUT
Drilling / Holing	Transfer the member to the drill by crane, conveyer, or by other means; drill the hole, using for instance, a radial drilling machine. Machines equipped with multiple drilling heads speed up the drilling process, several holes are drilled simultaneously.	Radial drilling machine	CUT
Finish	Remove unacceptable levels of hardness at the edge of the member by milling.	Surface machining and Milling machines.	FINISH

Shop Operation	Description	Equipments/Tools	Taxonomy/Operation
Assembly	Join the secondary components, end plates, stiffeners, etc. to the main steel elements. As a general role, shop connections are welded and site connections bolted.	Welding machines, cranes.	This part falls under the ASSEMBLY level
Painting	Paint steel assemblies and components. Paint spraying can be carried out manually or automatically.	Paint spraying machines; Paint brushes.	FINISH
Inspection	Ensure that the steel complies with the fabrication drawings and specifications. Check the overall dimensions, position of cleats, holes, weld and so on, to ensure proper alignment during site erection.	X-ray machine and measuring tools.	INSPECT

Assembly at the fabrication shop

As mentioned earlier, the fabricator preassembles steel parts and components to reduce the amount of work to be done on-site. This section will analyze the assembly operations of column 2A as they occur at the fabrication shop. The analysis is being done at the operation level. First, let us consider the components of column 2A subassembly. Column 2A consists of the main column (W24x104), base plate, end plate, four support plates, and two connection plates. All those components are joined together by welding at the fabrication shop. Then the subassembly is transported to the field to be erected.

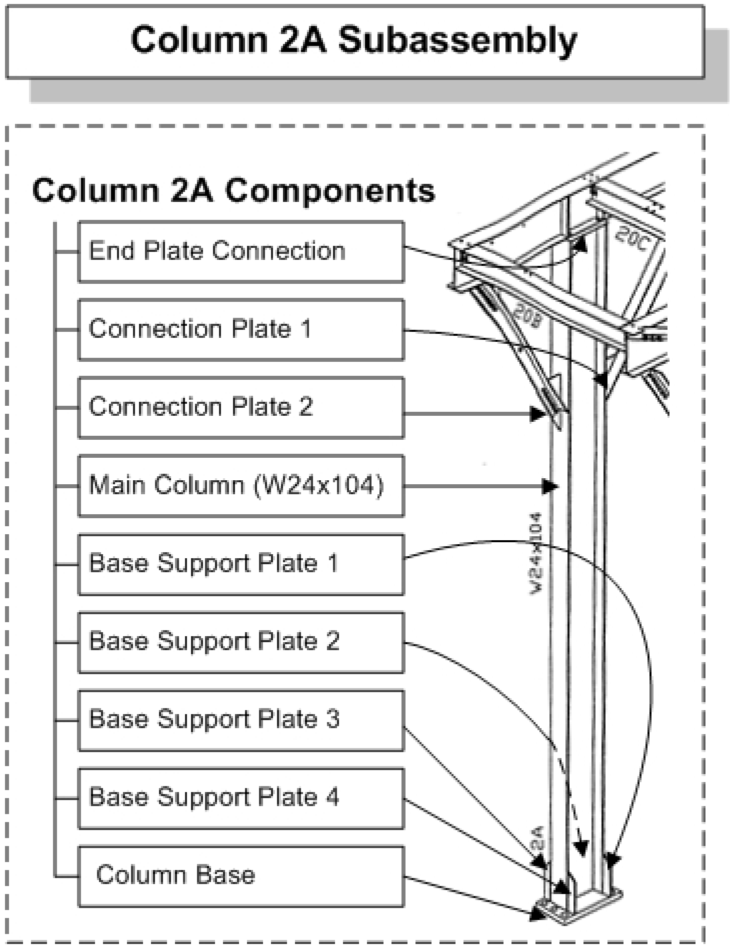


Figure 8.8: The components of column 2A subassembly.

Figure 8.9 and 8.10 illustrates the sequence of operations that leads to the realization of a subassembly, for instance column 2A. As depicted in Figure 8.9, once the pieces of steel stock for the main column arrive at the fabrication shop it will be unloaded 'MOVE' with and overhead crane, with magnetic devices, attached to a conveyor system. Then it will go through a linear process of operations including blast cleaning 'Finish', measuring and marking 'MEASURE', cutting to length and drilling with power saws and radial drills' CUT', milling and facing 'FINISH', and welding 'CONNECT'.

Temporary plates are bolted to the end plate of each column to provide a connection joint for the lifting line during erection. Those plates are removed once the column is secured into its final position.

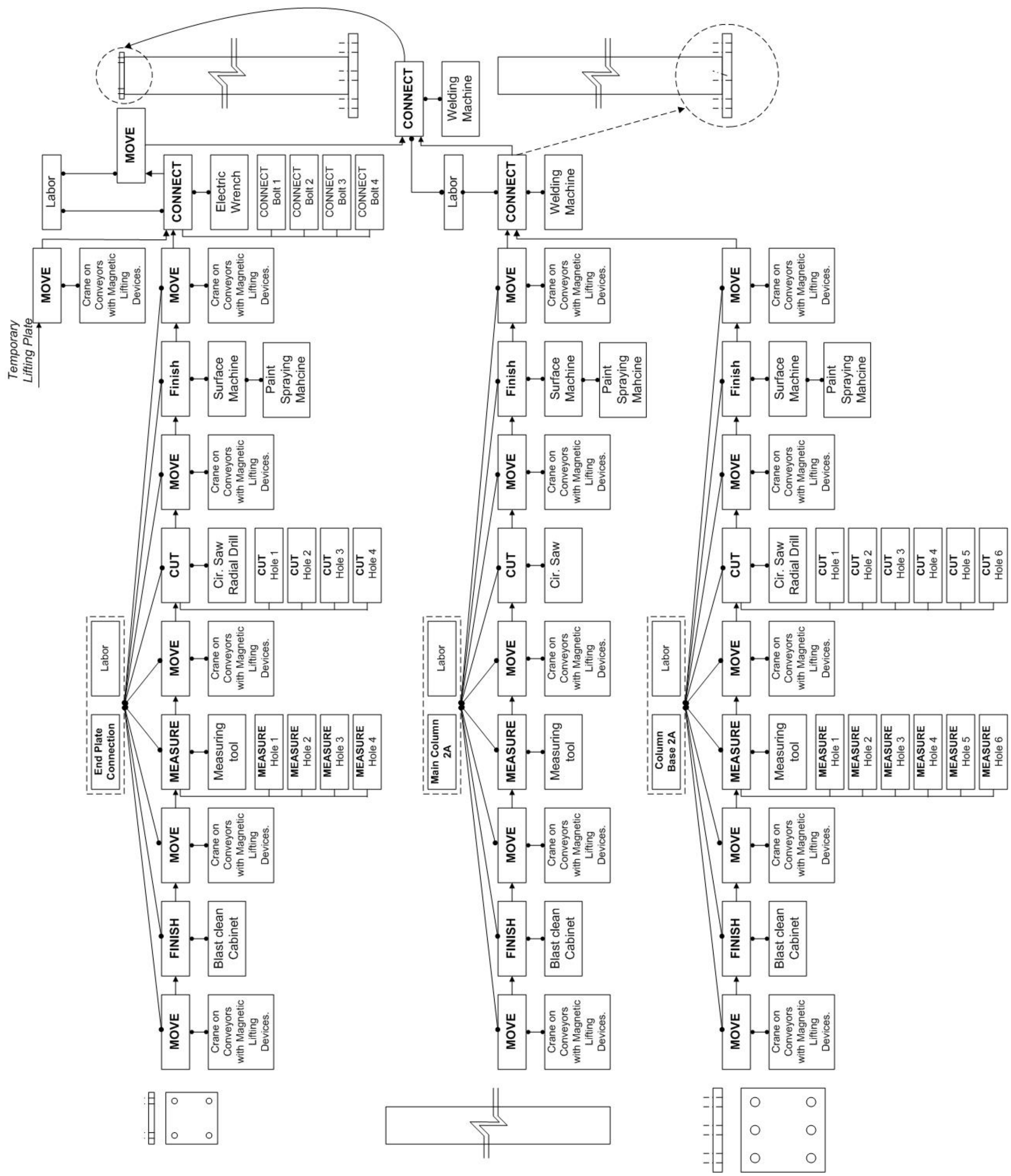


Figure 8.9: Part 1 of the sequence of operations at the fabrication shop for subassembly column 2A.

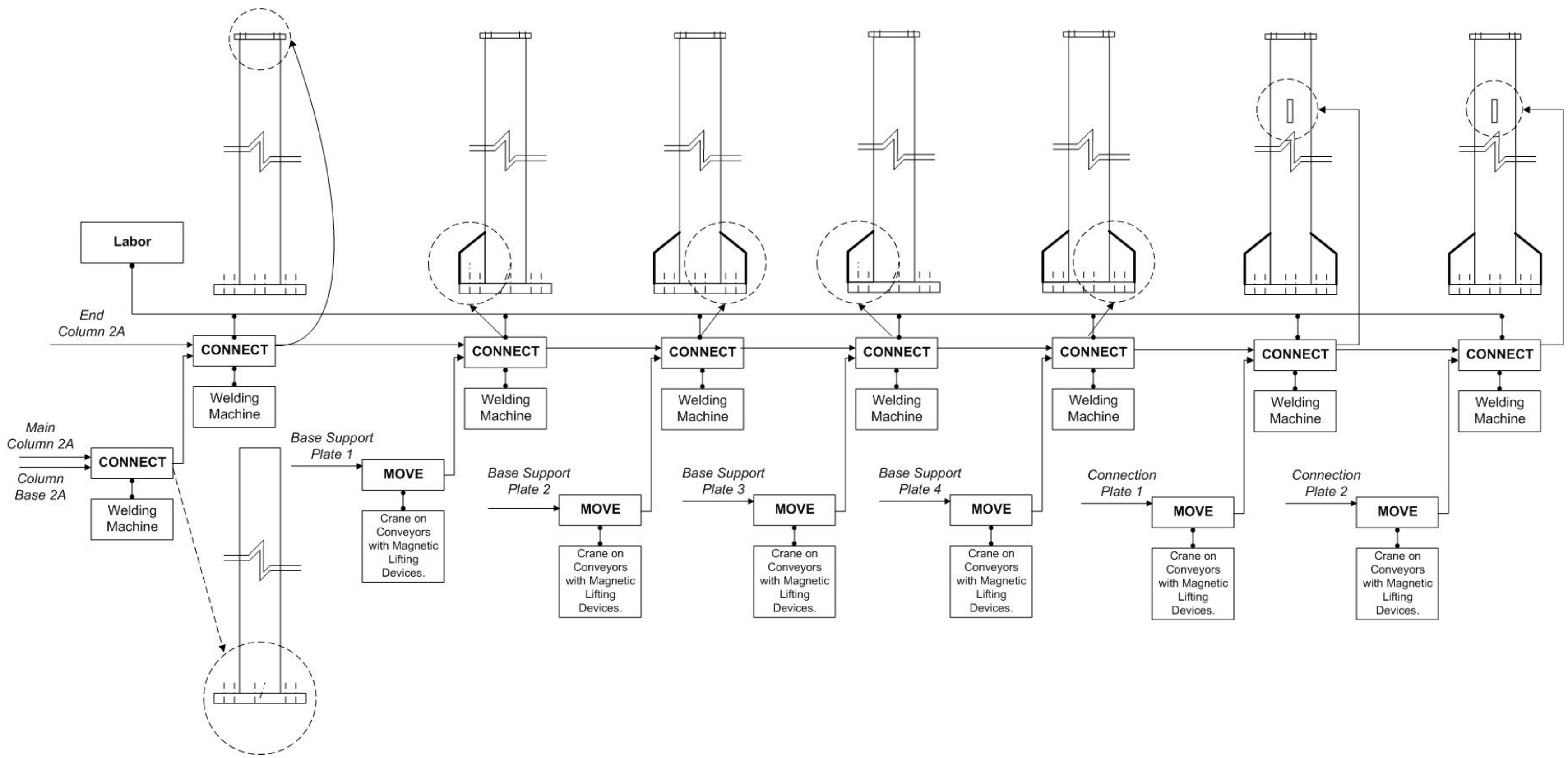


Figure 8.10: Part 2 of the sequence of operations at the fabrication shop for subassembly column 2A.

8.4.4.2 Site Erection

The erector is responsible for the assembly of the steel structure subassemblies and components on the construction site. Material delivery is a very important part of the erection process, thus it is highly recommended that the fabricator fabricate and deliver the steel construction elements in the same sequence as they are erected on site. Generally the site will have a lay down area where material can be stored until needed. However, just-in-time delivery should be coordinated for the heavier steel elements to minimize material handling on site.

The first planning step prior to the commencement of field operations is the development of an overall plan that lays out the erection sequence of the steel structure assembly. Figure 8.11, provides a network model that describes the overall plan and erection sequence of the major components and subassemblies of the steel structure. As shown in Figure 8.11, there are two parallel paths for the erection of the steel structure. While the first path starts with the erection of column 2A, the second path starts with the erection of column 1A. Once all column are erected beams erection takes place until the whole structure is erected according the network model.

Before the erection process commences, the foundation must be inspected and measured to check the leveling and alignment of the anchor bolts, see Figure 8.12.

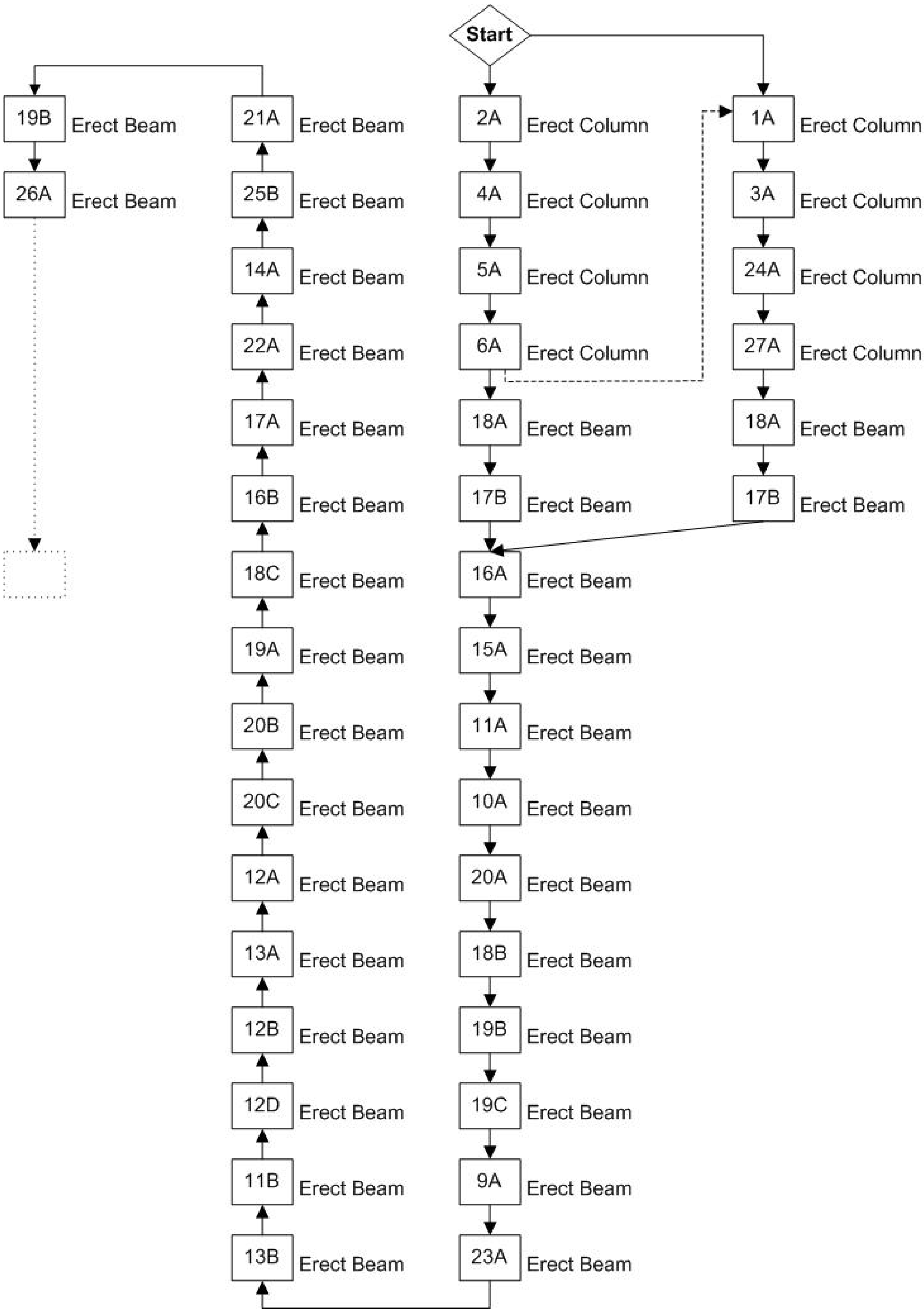


Figure 8.11: Representation model of the steel structure erection sequence.

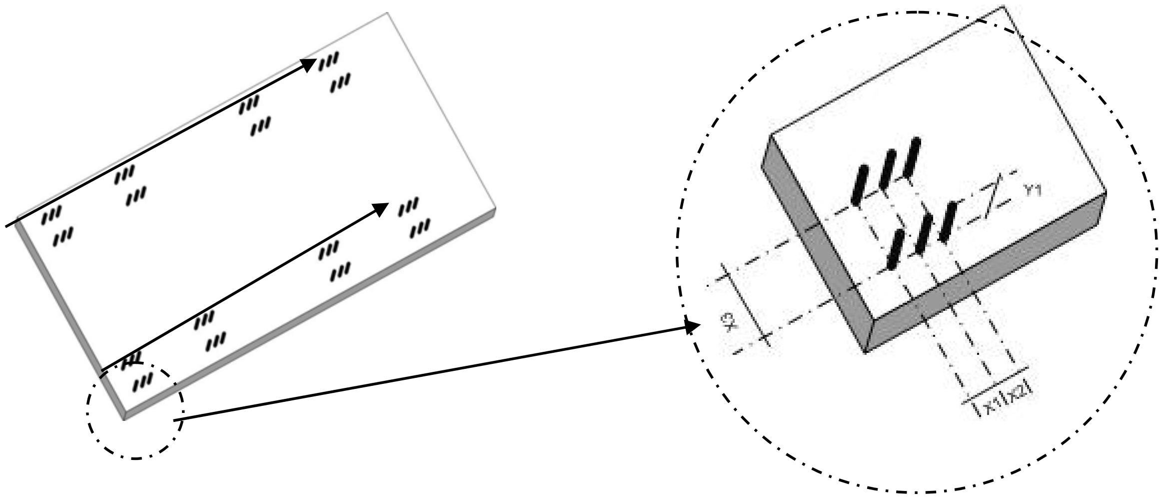


Figure 8.12: Checking the leveling and alignment of anchor bolts.

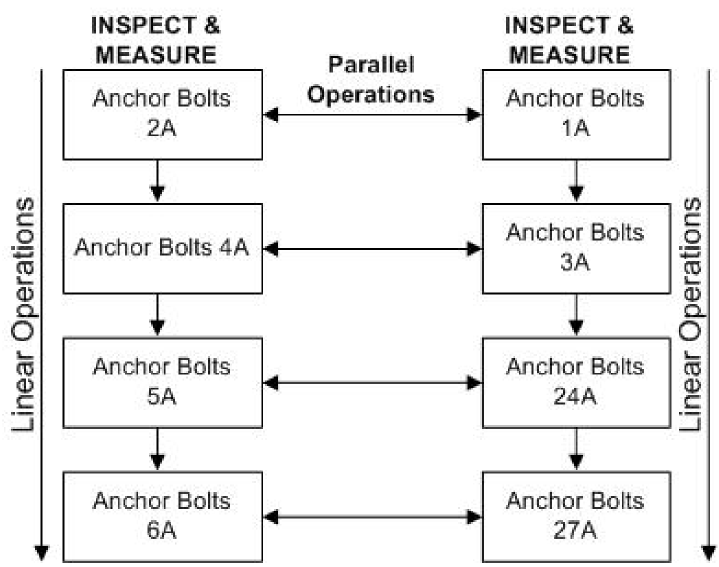


Figure 8.13: The linear and parallel inspection process.

The INSPECT/MEASURE anchor bolts operations are performed in linear and parallel processes. Figure 8.13 shows the sequence of operations for inspecting the anchor bolts for column 1A, 2A, 3A, 4A, 5A, 6A, 24A, AND 27A. For instance, the anchor bolts for column 2A is check in parallel with the anchor bolts for column 1A. Then the leveling of anchor blots 1A is checked with the leveling of 2A. The sequence of operations needed for checking and adjusting the position of the anchor bolts are shown in Figure 8.14.

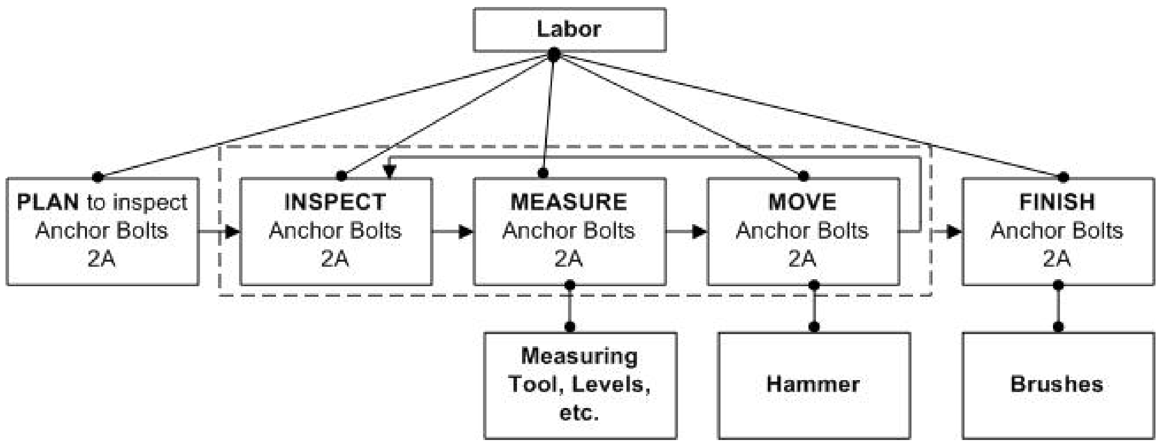


Figure 8.14: The operations needed for checking/adjusting anchor bolts for column 2A.

After the leveling and alignment checks are completed for the foundation and the proper adjustment have been made to anchor bolts, the foundation must be cleaned from any contamination. Table 8.4 describes the pre-erection operations and the equipment and tools need for those operations.

Table 8.4: Foundation and anchor bolts checks prior to erection.

Site Operation	**Description**	**Equipment/Tools**	**Taxonomy / Operation**
Plan work	Collect and review foundations and steel fabrication drawing.		PLAN
Inspect and measure	Inspect the column bases to check the leveling and alignment of the anchor bolts.	Measuring and surveying tools.	INSPECT MEASURE
Clean	Clean the foundations to ensure the cavities for the holding down bolts are completely free from contamination.		FINISH

The erection of steel subassemblies and components can commence after the foundations and anchor bolts are checked. The erection sequence for the entire steel structure assembly is shown in Figure 8.11. The operations involved in the erection of column 2A are shown in Figure 8.15, which consists of the following major construction operations: PLAN, INSPECT, MEASURE, MOVE, and CONNECT. Furthermore, the operations model shown in Figure 8.15 can be reused over and over again to describe the erection model of most of the steel elements that make up the over all steel structure assembly.

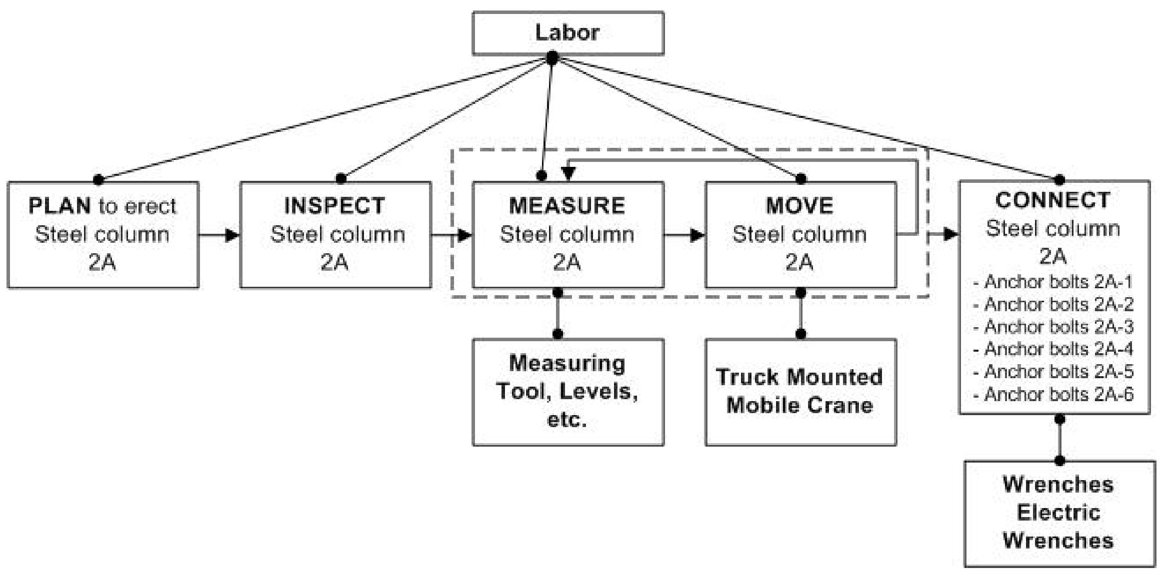


Figure 8.15: Steel erection operations model for Column 2A.

As depicted in Figure 8.16, it is common practice to start with lifting, a 'MOVE' operation, a column with a truck mounted mobile crane. The lifting operation can be represented by the 'MOVE' operation as described in the taxonomy. A light wire rope fixed to one of the steel elements is usually used to control the swing of the element. Then the column will be positioned into its final location, also part of the 'MOVE' operation. Once the leveling of the column, 'MOVE and MEASURE' operations, is complete, all connections are then made permanent by tightening up all nuts, a 'CONNECT' operation.

Besides some minor changes, such as the number of bolts for a connection, the same model can be used to describe the construction operations needed for the erection of all steel subassemblies and components.

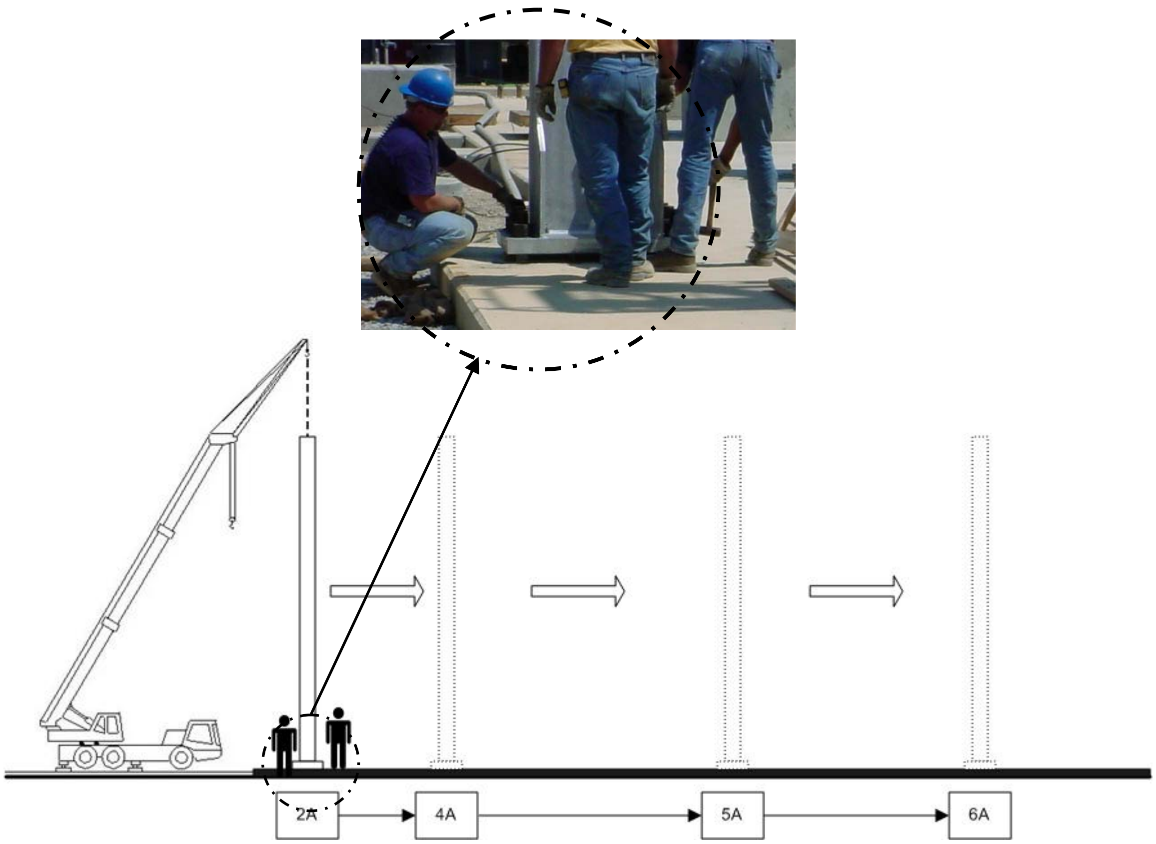


Figure 8.16: The erection of steel column 2A.

Table 8.5: Description, equipment and tools, and taxonomy representation of on site erection operations.

Site Operation	Description	Equipment/Tools	Taxonomy / Operation
Plan	Identify the column to be moved from those in the lay		PLAN

Site Operation	Description	Equipment/Tools	Taxonomy / Operation
	down area.		
Inspect & measure	Inspect and measure steel element.	Measuring tools	INSPECT MEASURE
Place	Move a steel element from the storage area to its final position according the erection drawings. The MOVE operations including the following: drop the crane hooks to the column; attach the hooks to the column; lift, swing, place the column; and position the beam into the final position.	Mobile crane Transport equipment	MOVE
Inspect	Check the bolts, nuts, and washers against the drawings. They must be exactly as indicated on the fabrication drawings and they must be clean and undamaged.	Visual inspection	INSPECT
Move	Install bolts exact location and position in drilled holes.	Torque wrench	MOVE
Move	Insert a hardened steel washer under the nut.		MOVE
Move	Position the nuts over the washer.		MOVE
Connect	Connect the nuts by rotating them around the bolts. Don't tighten the nuts to allow members flexibility.	Torque wrench	CONNECT

The focus of this example was to describe the fabrication, assembly, and erection of the steel structure, shown in Figure 8.2 and 8.4, as they occur at the fabrication shop and the construction site. The intention was to illustrate by example that the proposed taxonomy is capable of describing and modeling the needed construction operations and processes to complete the erection of the steel structure. Thus the flow charts and the process models developed for this example only reflect the way that the work is typically being carried out at the fabrication shop and the construction site.

8.5 EXPLORATORY CASE STUDY (HRSG ERECTION)

8.5.1 INTRODUCTION

In Section 8.4 we presented an example that validated the capabilities of the developed taxonomy to model construction operations. The focus of the example was on utilizing the developed taxonomy to model the construction operations involved in the fabrication, assembly, and erection of the steel structure. This section presents a exploratory case study that involves not only the implementation of the developed construction modeling system but it facilitates beyond existing methods to show the potential use of the developed modeling system to model, analyze, and improve construction operations.

The research strategy adopted in this case study was action research. As depicted in Figure 8.17, it is a cyclic process, involving investigation of the problem, planning, action, implementation, and evaluation of the results.

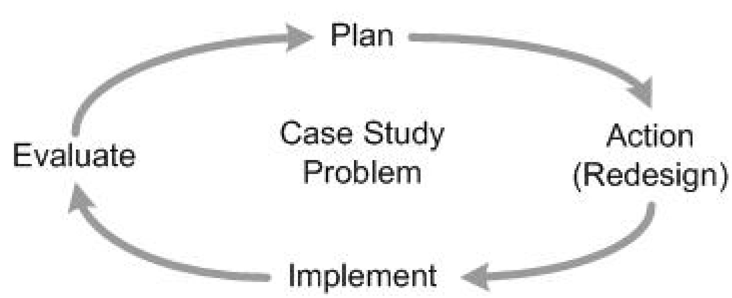


Figure 8.17: Action research process.

8.5.2 EVALUATION OF CASE STUDY - EVALUATE

The exploratory case study was taken from a two on one combined cycle power generation station project which includes two LM6000 combustion turbines, two Heat Recovery Steam Generators (HRSG), a single condensing steam turbine generator, a steam condenser, a cooling tower, a 115 switchyard, water treatment facility, plant operations building, and gas compressor building.

As shown in Figure 8.18, the project site is surrounded on all four sides by existing structures and major roads. The existing infrastructures and 115 kV power line provided for a very tight construction site. Due to site and schedule constraints and material deliveries, access to install components was extremely limited. Material staging areas were confined to three locations remote from the construction site; the primary staging area was approximately one mile away.

The HRSG erection and its interrelated construction operations were identified as a good candidate for this case study. This project includes two identical HRSGs. Each HRSG measures 115 ft long, 60 ft tall and 11 ft wide with a stack that towers to 92 ft. The erection process of each HRSG is essentially the same. It is a complex process, involving heavy steel structures erection, steel platforms and supports, large bore and small bore piping, steam drums, vessels, sensitive electrical equipments, and mechanical equipment, as shown graphically in Figure 8.19. The HRSG's heavy steel structure and casing erection is the focus of this case study.

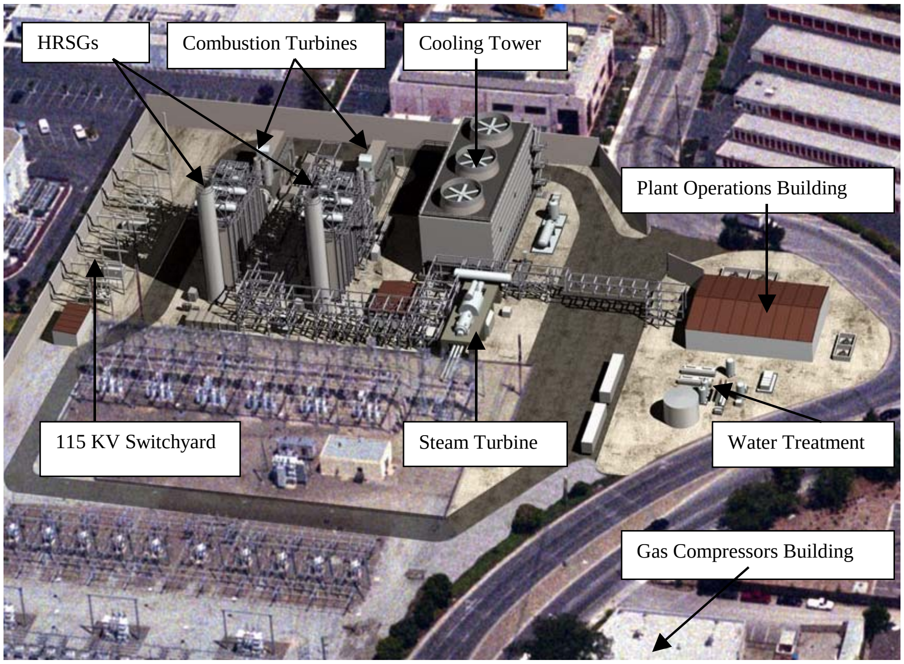


Figure 8.18: 3D view of the combined cycle generation project including the surrounding environment.

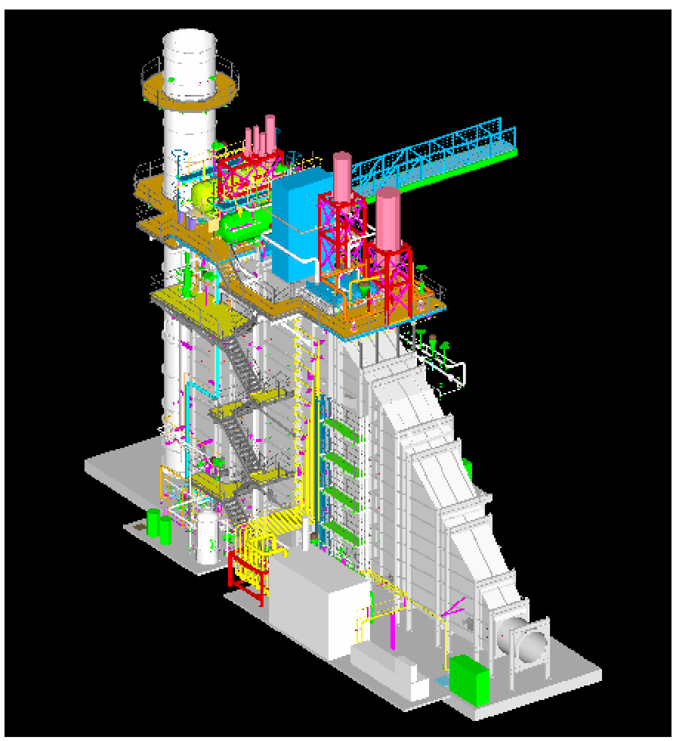


Figure 8.19: 3D model of the major HRSG components.

On paper, the HRSG erection process looks like a routine job. What makes this erection complicated is the small site and its logistical constraints in which crews has to erect the HRSG massive components.

The first major obstacle that faces construction managers during the course of the HRSG erection is outlining the logistical details regarding the crane locations and their movement along with the availability of on-site material staging areas. Logistics become extremely important especially when presented with construction sites with several constraints, as in the case of the construction site show in Figure 8.20.

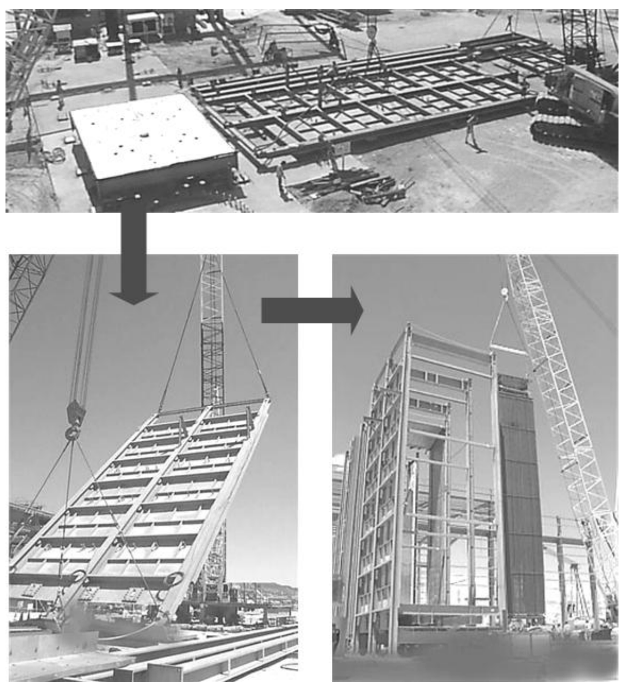


Figure 8.20: HRSG heavy steel, casing and pressure modules assembly.

As illustrated in Figure 8.20, the in-field assembly of the HRSG heavy steel, casing and pressure modules requires relatively a large construction site that provides enough area for material staging and cranes movements.

The second major obstacle is the constant demand to shorten the construction schedule in order to meet the market need. In an effort to overcome some of the obstacles a thorough understanding of the HRSG design and erection processes is needed. This can be achieved by utilizing the developed taxonomy to model, evaluate, and select HRSG prototypes that will potentially improve the in-field HRSG construction operations.

8.5.3 CASE STUDY GOALS - PLAN

In order to improve the in-field HRSG construction operations and produce a value adding models it was necessary to be as realistic as possible. Before starting any modeling analysis of the HRSG erection, the overall goals of the model were determined. The goals served as the modeling objectives throughout the modeling course of this case study. The goals are outlined as follows: Minimize material handling at the construction site, reduce the overall project schedule, maximize efficiency, and maximize concurrency.

8.5.4 PRODUCT BREAKDOWN STRUCTURE

One of the most useful tools of the developed taxonomy is the ability to model construction operations at several levels of details to form a hierarchy. By linking one model to another you create a parent-child relationship. Changes applied to the child are also transmitted to the parent. By linking more models to both parent and child models complex hierarchies can be created to represent complex construction operations.

This section provides an overview of the product breakdown structure of the project chosen to illustrate the use of hierarchical modeling. The development of the product breakdown structure is a dynamic process that evolves into a more meaningful structure in conjunction with the development and analysis of the construction operations models. In other words, the development processes of the product breakdown structure and their associated the construction operations models are mutually linked. The rational behind this approach is in order to improve product delivery in general and construction operations in specific an effective integration is required between construction operations and design processes of product, assemblies and components. The developed taxonomy supports this rational.

The product is a combined cycle power plant that was divided into eight main assemblies: (1) HRSG, (2) combustion turbines, (3) cooling tower, (4) steam turbine, (5) water treatment facility, (6) gas compressors, (7) plant operations building, and (8) switchyard.

The HRSG assembly was broken-down into of subassemblies of which the HRSG main steel structure and ducts were the focus of this case study. Several alternatives for modeling the HRSG main steel structure and ducts sub-assemblies were considered by the researcher and the most promising alternative was selected. The selected alternative calls for dividing the HRSG main steel structure and ducts into ten sub-subassemblies, as illustrated in Figure 8.21. Furthermore, each one of the ten sub-subassemblies was broken down into major components. Several design alternatives of the sub-assemblies components were also examined. Figure 8.22 illustrates the major components for HRSG subassembly 01-01-08.

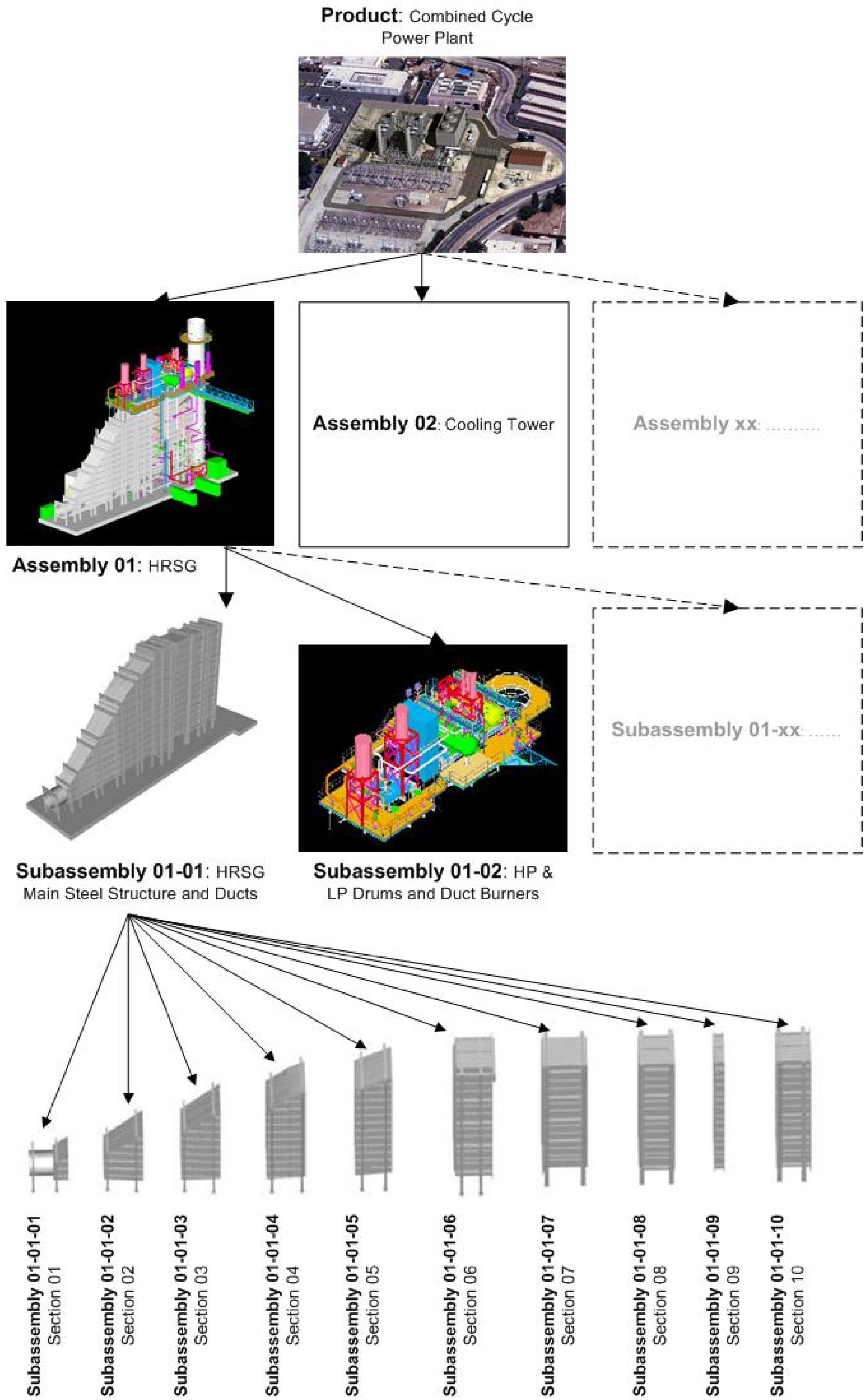


Figure 8.21: Product, assemblies, and subassemblies breakdown structure.

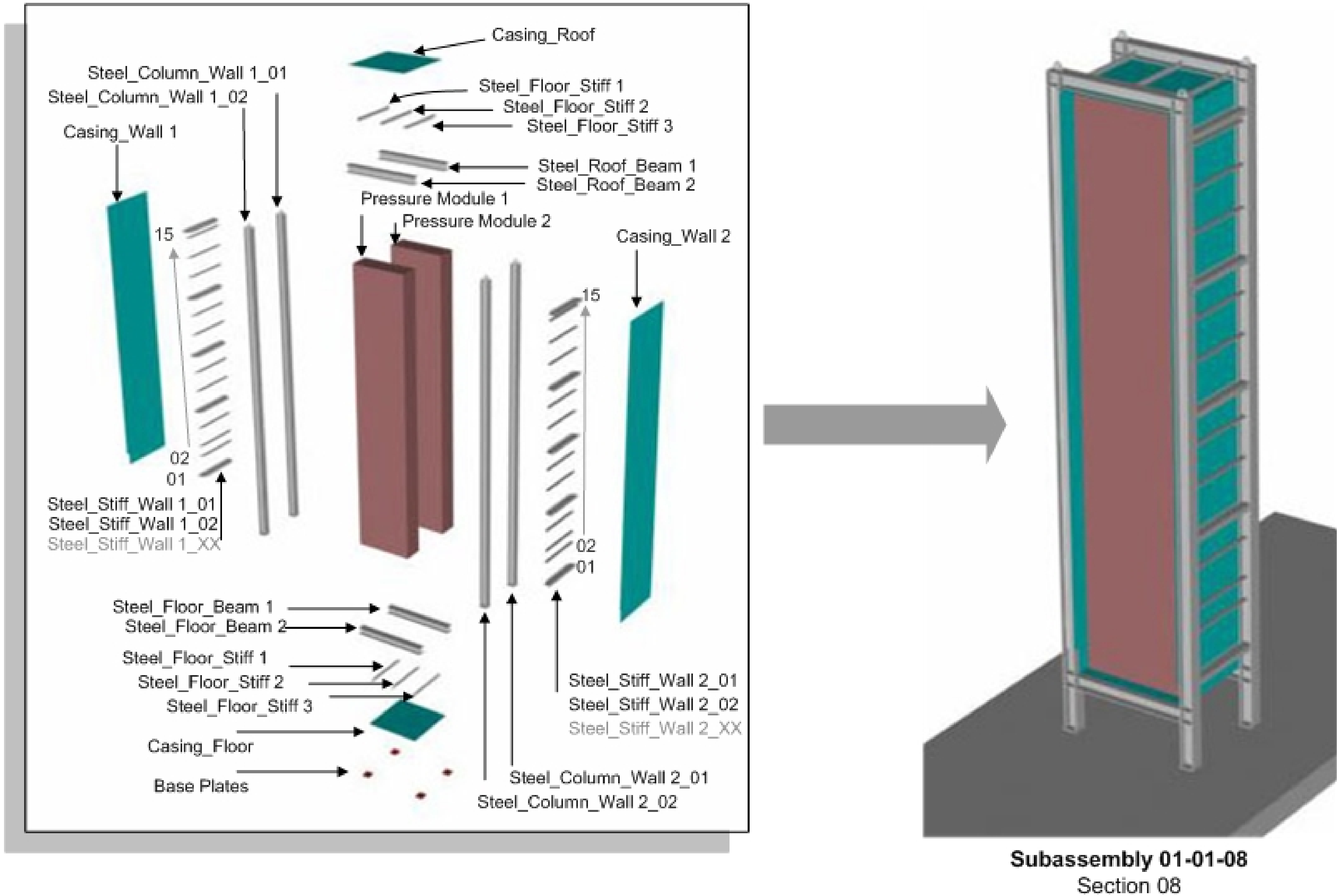


Figure 8.22: The major components of HRSG subassembly 01-01-08.

8.5.5 PROCESS MODELING

The product breakdown structure was presented in the previous section. This section clearly demonstrates the ability of the developed taxonomy to produce hierarchical and prototype models that can be reused to create models that describe the construction operations involved in the steel structures erection process. The advantages of using hierarchical breakdown of product into subassemblies and components and the use of prototype sub-models can be clearly perceived in this section.

Figure 8.23 depicts a prototype sub-model that represents the construction operations involved in the fabrication of the steel components. The prototypes sub-models could be used to model any steel shop fabrication process.

Likewise, the construction operations involved in joining two steel components, a steel component and a steel subassembly, or two steel subassemblies to create a higher level subassembly are modeled in the steel subassembly prototype sub-model, as illustrated in Figure 8.24.

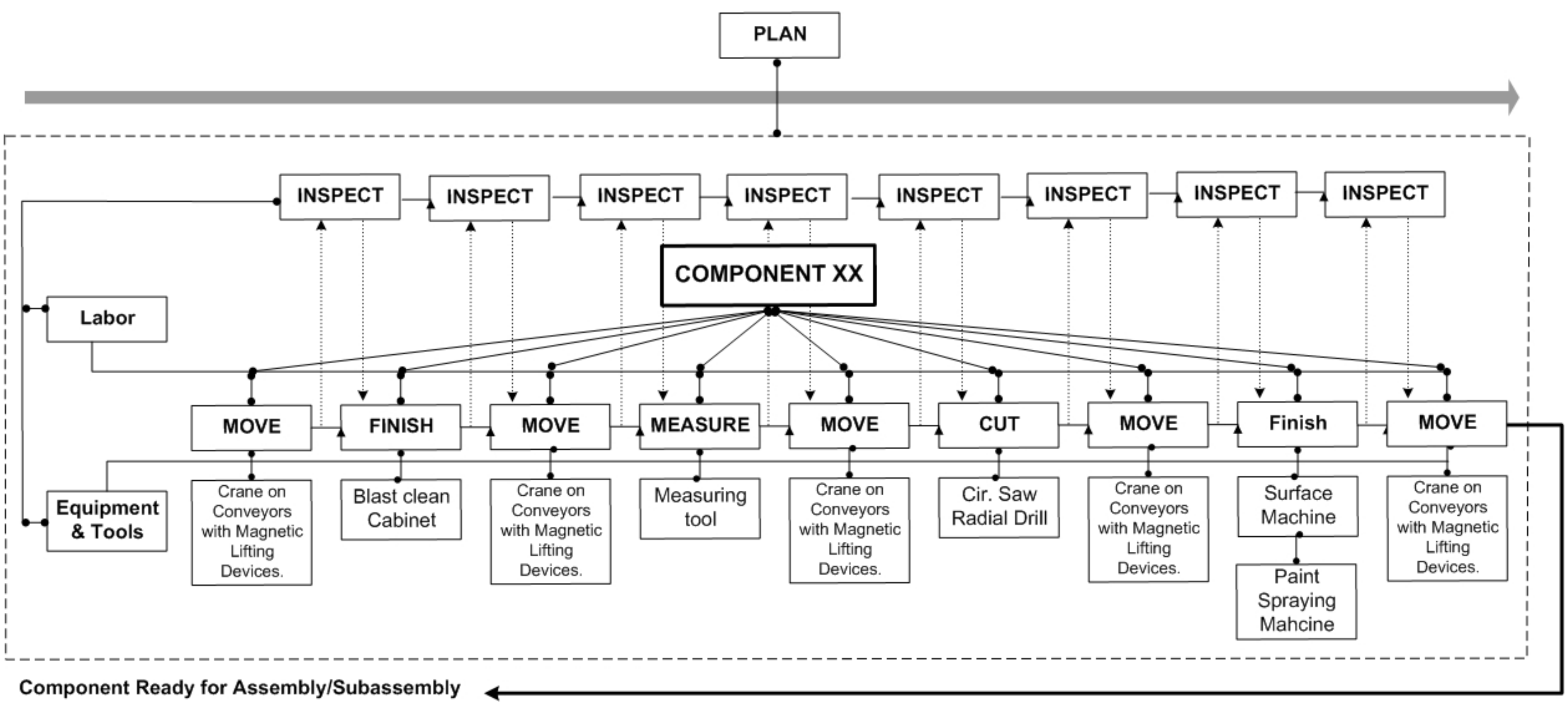


Figure 8.23: Typical steel component sub-model.

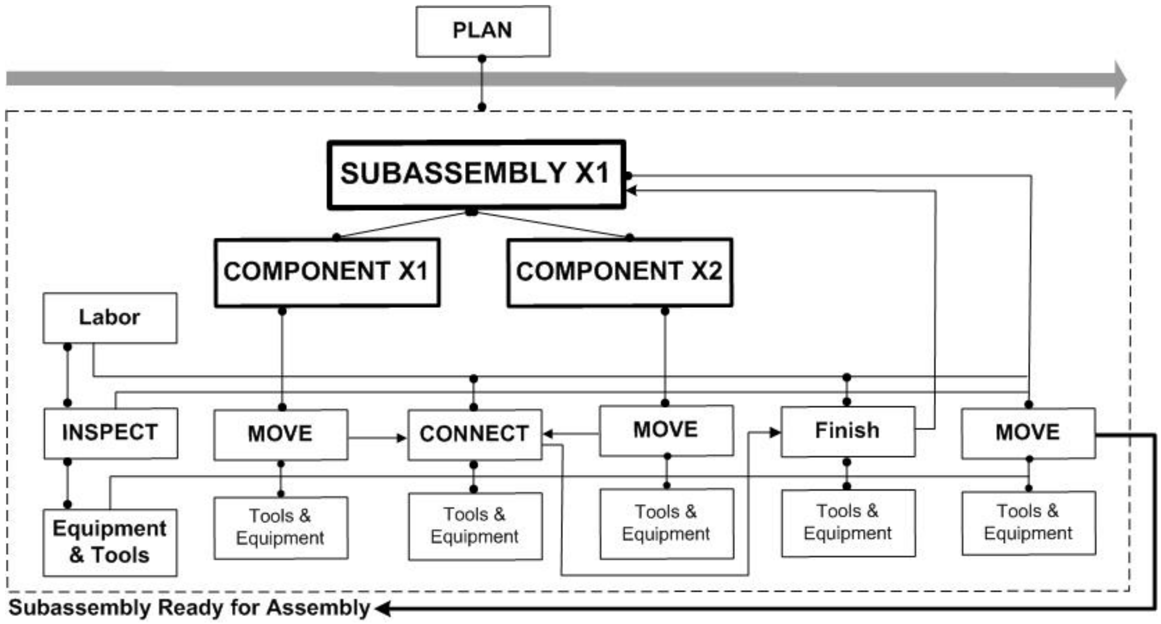


Figure 8.24: Prototype steel subassembly sub-model.

The prototypes sub-models can usefully be modified to create different prototype assembly models. For example, the subassembly prototype sub-model was used to create the base plates installation model. The base plates installation is part of subassembly 01-01-08. The intent of the model is to describe in a structured way the construction operations involved in connecting the base plates to the HRSG foundation. The subassembly prototype models were structured in such a way that both components are linked to a separate MOVE operation. Hence the foundation is placed in its final location; there is no need for it to be linked to a MOVE operation. Therefore, the subassembly prototype sub-model was slightly modified by converting the MOVE operation linked to the COMPONENT HRSG foundation to a dummy operation, as depicted in Figure 8.25.

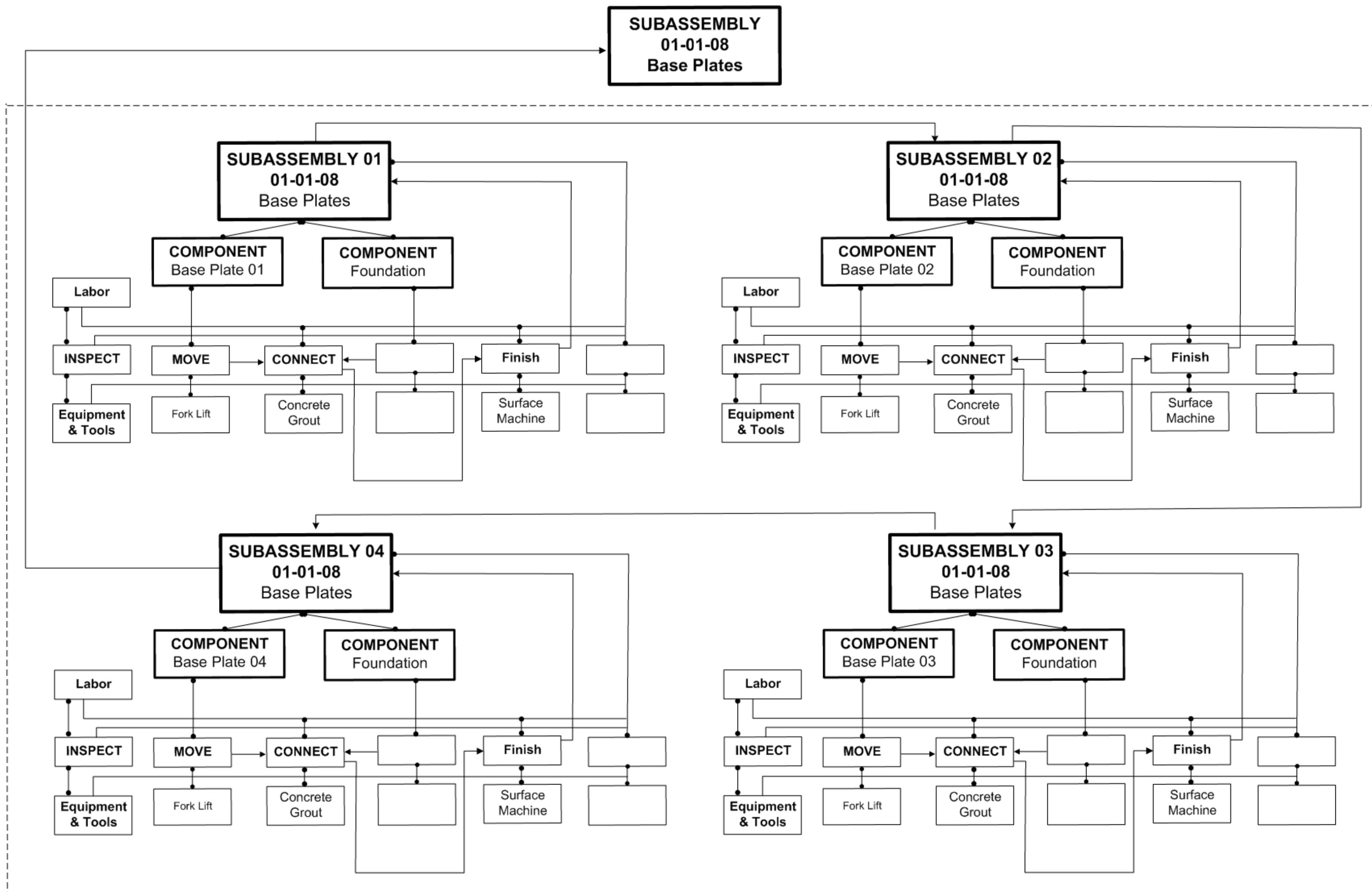


Figure 8.25: Base plates installation sub-model.

A dummy operation, represented in a blank box, can be defined as a modeling object that do not affect the in any way the modeled construction operations and is only needed to simplify the modification of the prototype sub-models. The ability to convert unused construction operations in a prototype to a dummy operation should preserve the modeling logic and make the prototype models more practical to use. The use of the developed sub-model prototype for steel joining components should simplify the modeling steel construction operations.

Figure 8.26 and 8.27 demonstrate the use of the subassembly prototype sub-model to create a higher-level subassembly model. Subassembly models were developed to identify the needed assembly components and the associated repetitive construction operations to realize the final assembly. The subassembly models then were evaluated and improved utilizing the action research method.

Subassembly 01-01-08 wall 1 consists of two columns and fifteen steel stiff components and steel casing. The same set and sequence of construction operations are used to assemble any two components of the wall 1 subassembly. MOVE and CONNECT operations are performed repeatedly to complete the wall 1 subassembly.

Repetitive operations are generally more suitable and more efficient to be performed in fabrication shop. Fabrication shops can be arranged in way that is similar to flexible manufacturing assembly lines. This will give greater flexibility to the construction process than is possible with current stick-built techniques.

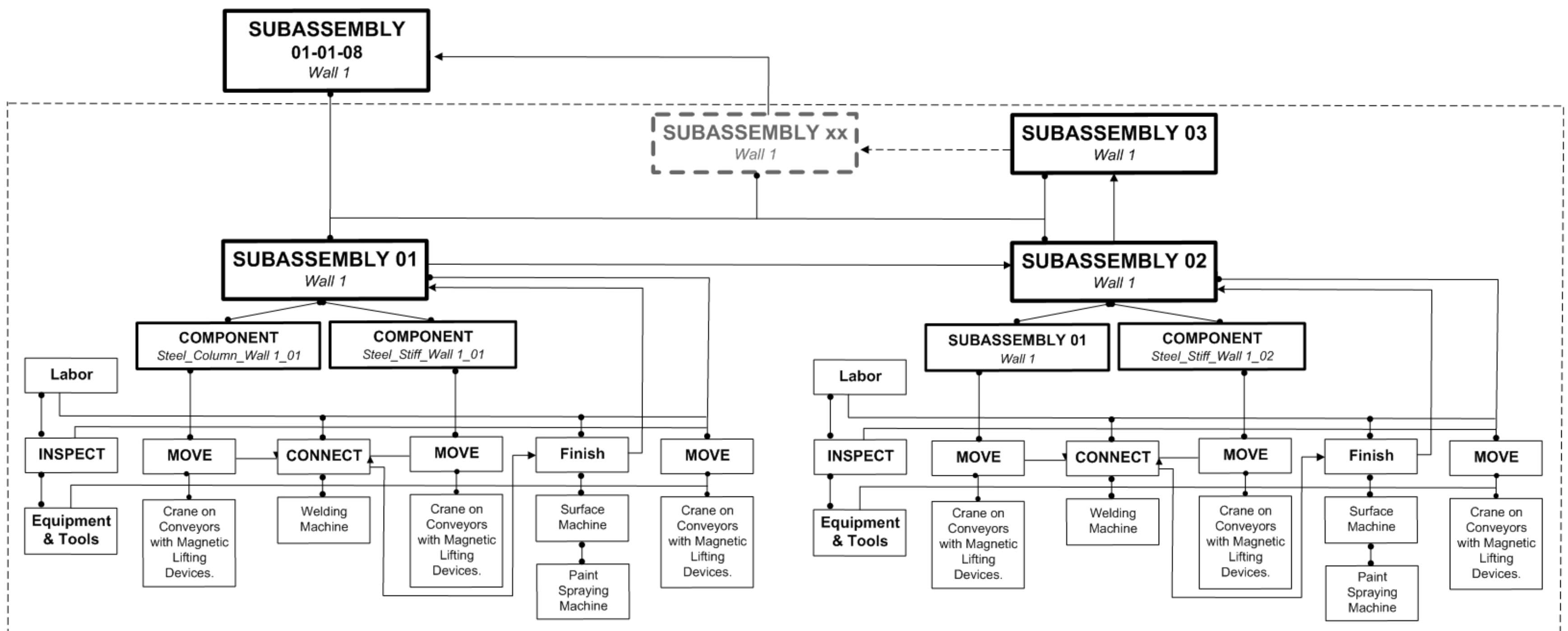


Figure 8.26: Wall 1 of subassembly 01-01-08 erection sub-model.

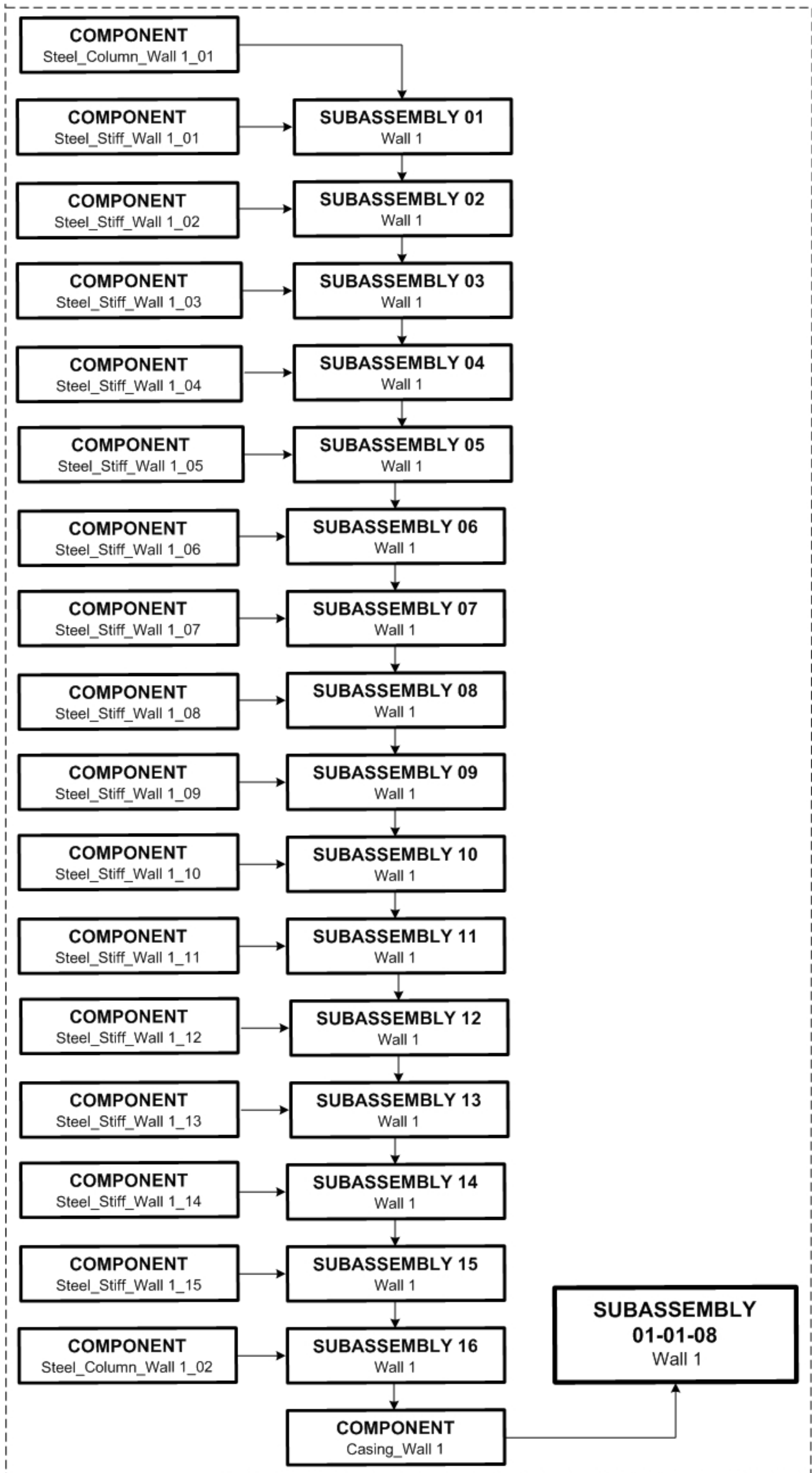
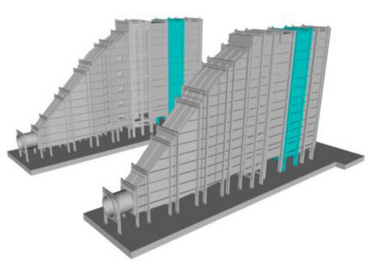
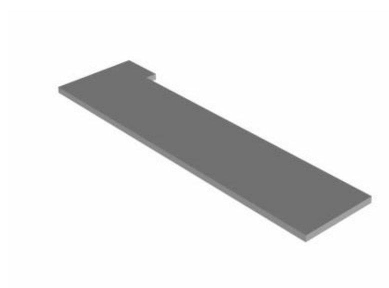
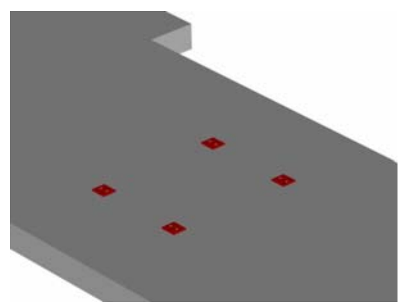


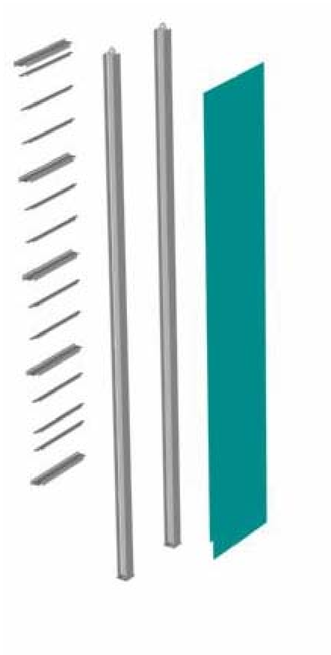
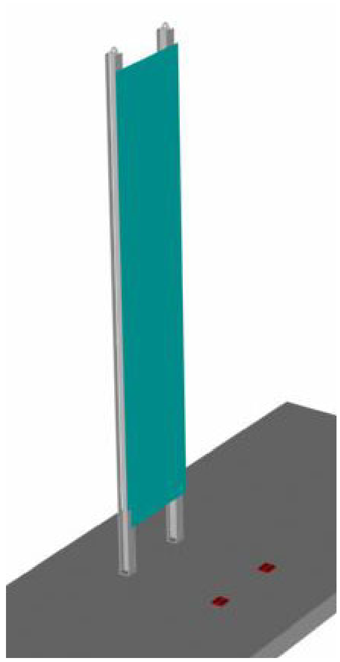
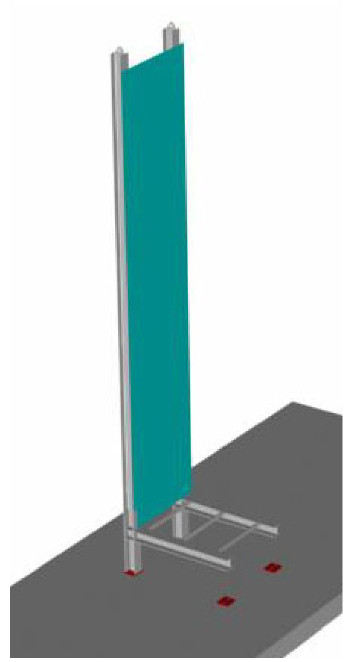
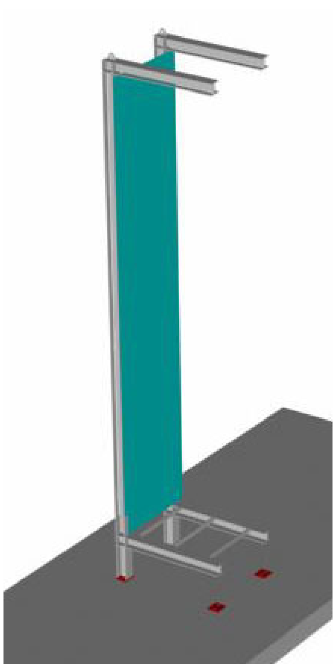
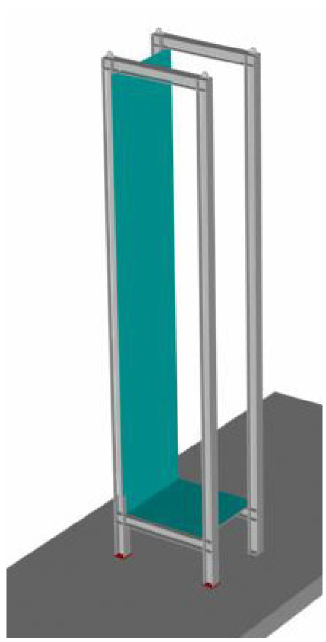
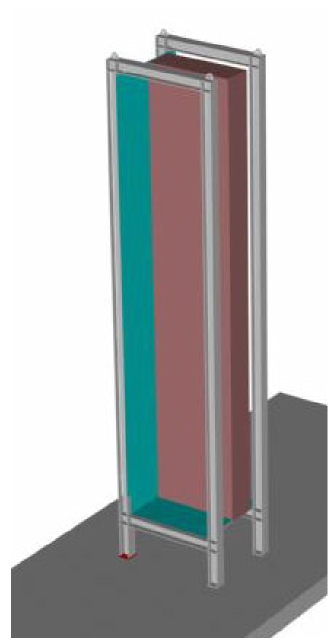
Figure 8.27: Subassembly 01-01-08 Wall 1 Model.

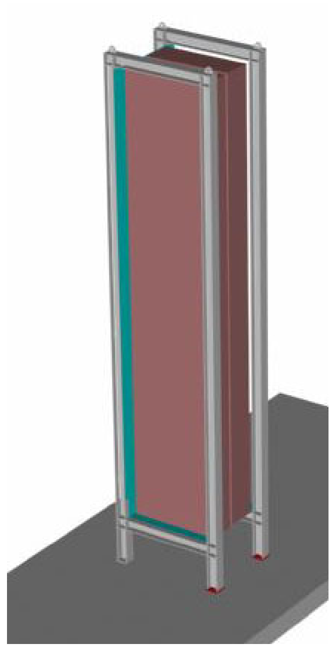
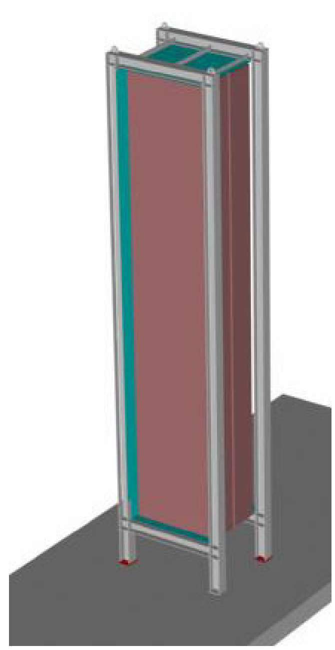
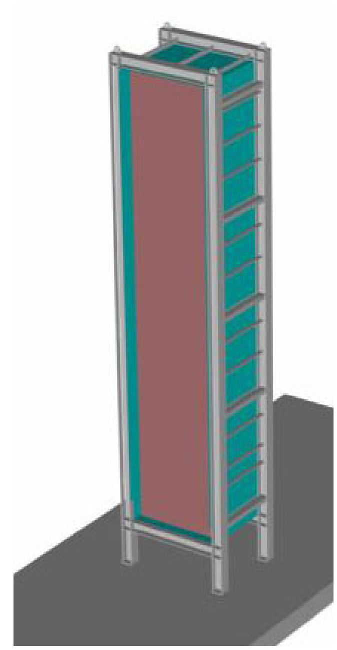
Table 8.6 presents graphical representation of the HRSG subassembly 01-01-08-erection process. It represents typical in-field erections of HRSGs. The floor structural steel is erected then one side of the HRSG wall including the casing is erected. Temporary steel is used to support the erected steel and casing until the pressure modules are installed. Then the second HRSG wall and roof casing is erected.

The graphical representation shows only one section of the HRSG that corresponds to the product breakdown structure described in section 8.5.4. Hence if the typical HRSG configuration focuses on the structure of the whole HRSG wall rather than on one section, the typical HRSG section configurations might be different from the one shown in Table 8.6.

Table 8.6: Graphical representation of HRSG subassembly 01-01-08 erection process.

		
HRSG Assemblies	HRSG foundation	Sole plates

		
Wall 1 Components	Install Wall 1	Install Floor Steel
		
Install Roof Support Steel	Install Wall 2 Support Steel	Install Pressure Module 1

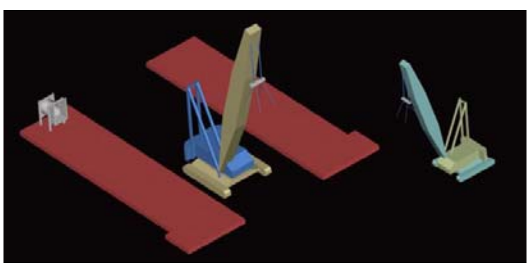
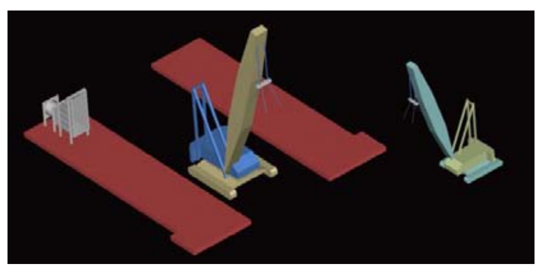
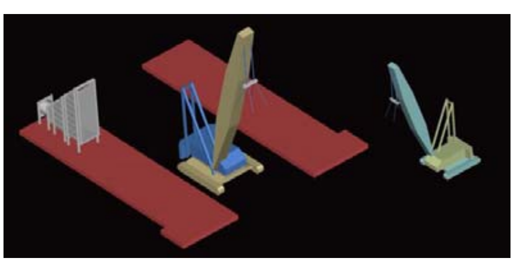
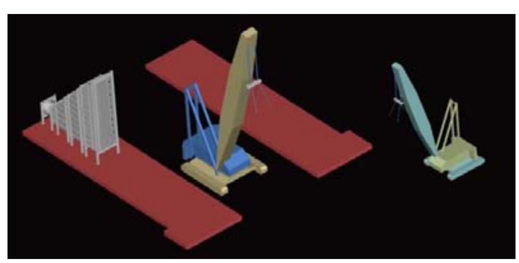
		
Install Pressure Module 2	Install Roof Steel &Casing	Install Wall 2 Steel & Casing

3D models of the HRSG subassemblies and their associated components were developed to study the HRSG erection modeling alternatives using AutoCAD 2000 and AutoDesk 3ds max. The HRSG 3D models were heavily used to investigate several HRSG design alternatives to identify improvement opportunities for on-site construction operations. On-site construction improvements were achieved by utilizing off-site prefabrication and pre-assembly techniques. The investigation was conducted in accordance to the goals identified in Section 8.5.3.

Shortening the project construction schedule, minimizing material handling, and maximizing efficiency are possible to achieve by utilizing concurrent engineering and construction and initiating multiple parallel construction task paths. Creating multiple parallel construction paths offers opportunities for schedule reduction and requires detail planning and analysis of the involved construction operations. The multiple parallel construction paths can be realized by use of prefabrication, pre-assembly and modularization techniques. Modularization techniques involve engineering and construction, and as such, require early implementation in the design process. Therefore construction operations should be analyzed during the early design stages to identify opportunities for construction design improvement.

The logistical details, the product components, and the construction operations for several HRSG erection alternatives were analyzed. The most promising alternative was selected as illustrated in Table 8.7. The sequence of handling, lifting, and installation of the HRSG large subassemblies on-site are the most complex challenges and needed further analysis to make the selected HRSG assembly breakdown structure alternative feasible to achieve.

Table 8.7: Graphical representation of HRSG subassembly 01-01 erection process.

	
Installation of HRSG Subassembly 01-01-01	Installation of HRSG Subassembly 01-01-02
	
Installation of HRSG Subassembly 01-01-03	Installation of HRSG Subassembly 01-01-04

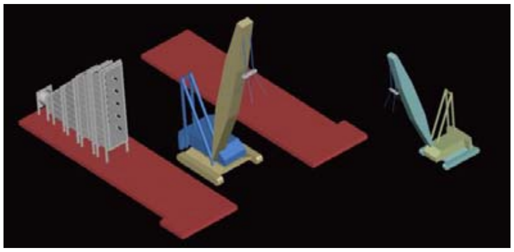
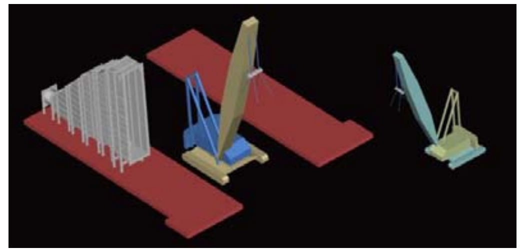
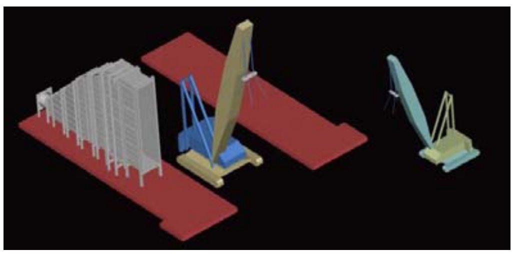
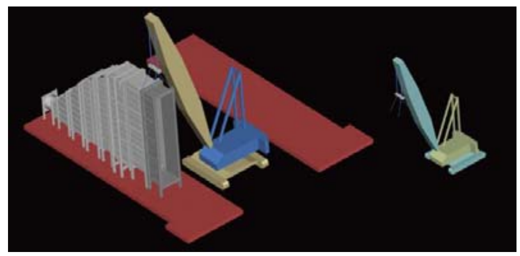
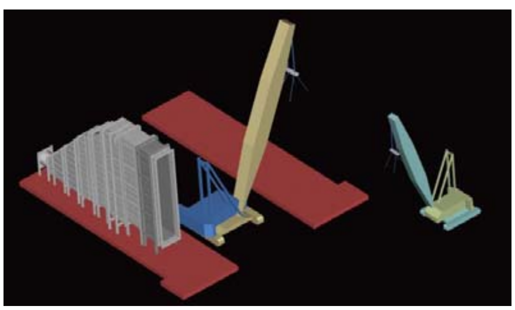
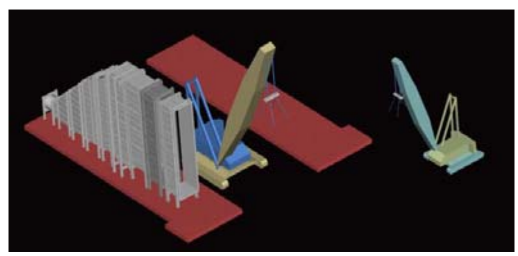
	
Installation of HRSG Subassembly 01-01-05	Installation of HRSG Subassembly 01-01-06
	
Installation of HRSG Subassembly 01-01-07	Installation of HRSG Subassembly 01-01-08
	
Installation of HRSG Subassembly 01-01-09	Installation of HRSG Subassembly 01-01-10

Figure 8.28 illustrates the use of the 3D modeling in conjunction with the developed taxonomy to evaluate construction operations and several HRSG assemblies configurations. As changes were made to the HRSG assembly configurations the cranes capacities and locations were also changing. The locations and sizes of the cranes are critical when dealing with such a small construction site. Therefore, 3D models and

simulations are required to validate the product and process breakdown structure alternatives.

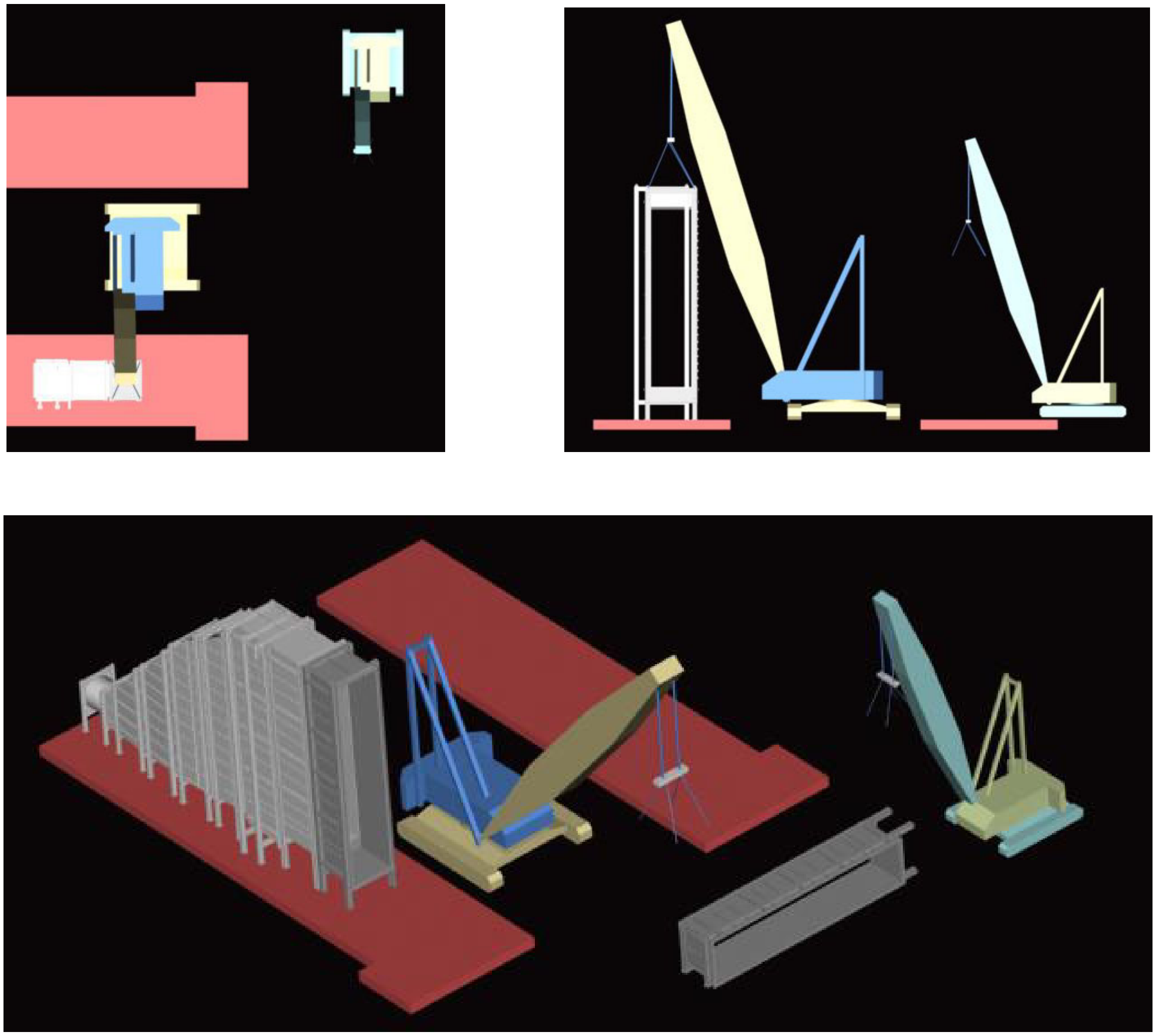


Figure 8.28: Graphic representations of HRSG subassembly 01-01-08 erection process.

Figure 8.29 shows the 2D representation of the lifting sequence and the lifting and tailing cranes measurement.

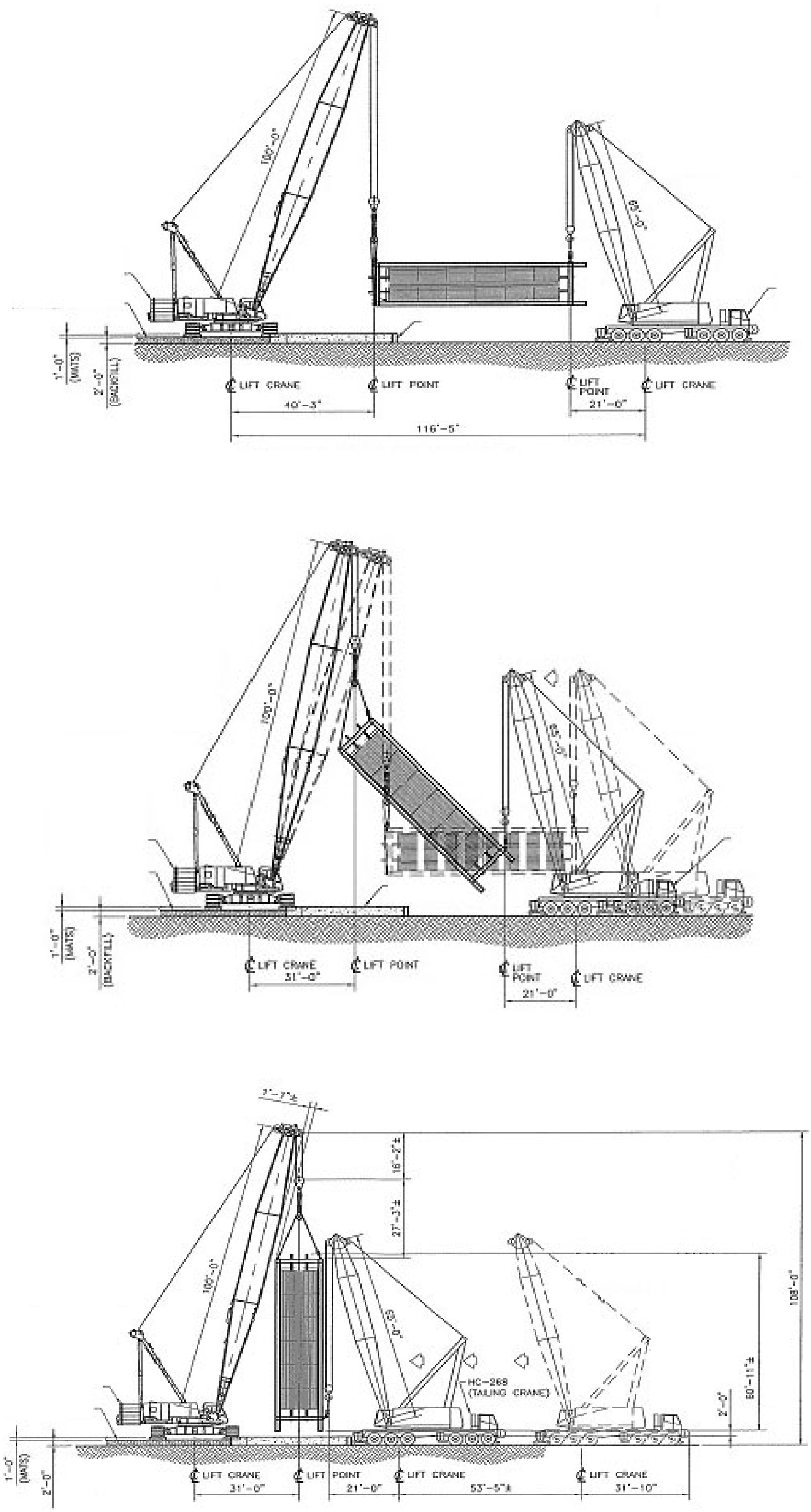


Figure 8.29: HRSG subassembly lifting process.

The simulation and modeling analysis showed that prefabrication and pre-assembly operations could be performed off-site. This significantly reduces the number of repetitive field erection operations to the point where only few on-site operations are needed to complete the erection of the HRSG main steel and ducts.

The larger HRSG assemblies create new connection schemes that can be evaluated and analyzed to identify opportunities for on-site construction automation. For example, joining the assemblies could be automated by using robotic welding machines.

The main conclusion drawn from the HRSG model development and analysis is that improvement to construction operations requires detail modeling of construction processes and rethinking the design and engineering process, with the goal of improving the overall project delivery in mind. The developed taxonomy supports this goal by providing a structured construction language to model and analyze construction operations at several level of detail. In addition, the developed taxonomy enhanced the environment for modeling, analyzing, and integrating the total engineering, procurement, and construction phases of a project. Furthermore, by utilizing the developed modeling system some barriers between engineering and in-field construction can be lifted allowing improvement of construction operations to optimize the design, procurement, and fabrication process.

Additional modeling and analysis are needed to further improve the final construction operations involved in the HRSG main steel frame erection. This work initiated the realization of the usefulness of the developed taxonomy to model, analyze, and improve on-site construction operation. The developed case studies have validated with great confidence the potential use of the modeling system as a direct support tool for improving construction.

The finding of this case study is just the tip of iceberg. Ultimately, the construction industry will realize the need for such a modeling system to record, analyze, and improve construction operations, especially when standardization and modularization concepts are profoundly employed by the construction industry.

8.6 SYNOPSIS

Chapter Eight provides two practical case studies that validate and demonstrate the capabilities and potential uses of the developed taxonomy. The first case study describes the modeling process of the fabrication, assembly, and erection of a steel structure. The fabrication and erection processes are presented as they occur at either the fabrication shop or at the construction site. Product and process breakdown structures are also presented. The second exploratory case study shows the potential uses of the developed system to model, analyze, and improve the construction operations involved in HRSG erection. Further, Chapter Eight clearly demonstrates the capabilities of the developed taxonomy to generate hierarchical and prototypical models that can be used multiple times to describe the operations involved in any steel structures erection. 3D models of the HRSG assemblies are developed and heavily used to investigate several HRSG design alternatives and identify improvement opportunities for on-site construction operations. Improvements are realized by initiating multiple parallel construction paths utilizing modularization, off-site prefabrication, and pre-assembly techniques.

CHAPTER NINE: SUMMARY, CONCLUSION, AND RECOMMENDATION FOR FUTURE RESEARCH

9.1 SUMMARY

During the course of this research, and in writing this dissertation, there are some background factors that have been borne in mind. One is that identifying and narrowing the scope of work of the researched subject. Because of the wide variety of the subjects that requires immediate research attention in construction, the proposed scope of work at the early stages of this research development was too large to be addressed in one dissertation. Most researchers are ambitious and devote their effort to ask and answer all the questions in their field of study and continually strive to resolve most of the problems to and increase the level of understanding add value to the body of knowledge. Likewise, this research started with a broad subject and with the goal of improving the way we do construction today.

Motivated to find a way to improve construction, this research went through several considerations and reviews that included but not limited to topics such as construction modeling and simulation techniques, construction means and methods, physically-based modeling techniques, virtual reality modeling environments, construction automation and robotics, construction products and processes, and construction classification systems. The reviews focused on identifying the state of current research in the aforementioned subjects and to determine how they can be utilized to achieve the objectives of the research in this dissertation.

As the research moved forward, it became apparent that all the aforementioned research subjects are essential components of the total effort to improve construction; however, what was missing is a common denominator that links these technologies and areas of knowledge together and provide a standard mean of communication among the construction industry. The common denominator is a common construction language that provides the needed classification structure to represent construction products, assemblies, operations, etc. From this point forward the research direction was shifted to focus on the development of a common construction taxonomy that can be used for modeling, capturing, analyzing, and potentially improving construction operations.

The development of the common taxonomy was challenging and required identification and investigation of the major categories of knowledge related to construction operations modeling and representations. These types of knowledge were identified and researched as follows:

Modeling and simulation: In Chapter Two, general modeling and simulation systems that are popular in the construction community are described. Also, an overview of the current state of modeling and simulation techniques is presented.

Physically-based modeling: Chapter Three presents physically-based modeling techniques and their connections to the developed taxonomy. Literature on the applications of physically-based modeling techniques were found to be limited, therefore applications from other fields, such as mechanical engineering, industrial engineering, and computer graphics are also reviewed. Additionally, this chapter establishes the advantages of applying physically-based techniques to construction modeling applications.

Virtual environments: Chapter Four reviews the fundamentals of virtual environments and the application of virtual and 4D-CAD modeling approaches in construction. The advantages and limitations of these approaches in relation to the developed modeling system in this research are identified. Virtual environments are identified as excellent representation medium for visualizing construction operations.

Automation and robotics in construction: In Chapter Five, the potential uses of robotics and automation opportunities in construction are discussed. Also, the distribution of work between humans and tools and equipment based on their physical and information contributions are presented.

Classification of construction work: Chapter Six presents and analyzes construction work classifications at different levels of detail. The main purpose of the analyses is to identify which construction operations can be usefully modeled and the appropriate level of the model. Therefore, various classification methods that are used to identify automation opportunities in construction are examined. In addition, the product and process breakdown structures in manufacturing operations are reviewed.

The common taxonomy: In Chapter Seven, a common taxonomy for modeling construction operations is developed. First, the taxonometric hierarchy consists of seven levels of classification: product, assemblies and subassemblies, components, operations, processes, physics, and control. The seven hierarchical levels are established by examining the ways that construction field operations are being carried out. Second, six major blocks of construction knowledge are identified and information about the interaction processes that is required to model construction operations in a logical way are described. Third, schemes for modeling information in the construction domain such as aecXML and IFC's are presented. Then the developed taxonomy is partially mapped to the IFC standards to identify where both systems intersect or overlap and their advantages and limitations. Fourth, areas of potential concurrency between the design process and the developed taxonometric structure are presented. Also, a new concurrent classification structure is developed to usefully facilitate the use of such a structure during the various stages of design. The new concurrent classification structure distinguishes between two categories of design and construction phases: product-oriented phases and process-oriented phases. Finally, this chapter investigates the adaptability of the developed modeling system by increasing the scope of accountability to include cradle-to-cradle responsibility. Design chemistry and design for disassembly are discussed and an example for the disassembly of a steel structure is presented.

Exploratory case studies: Chapter Eight provides two practical case studies that validate and demonstrate the capabilities and potential uses of the developed taxonomy. The first case study describes the modeling process of the fabrication, assembly, and erection of a steel structure. The fabrication and erection processes are presented as they occur at either the fabrication shop or at the construction site. Product and process breakdown structures are also presented. The second exploratory case study shows the potential uses of the developed system to model, analyze, and improve the construction operations involved in HRSG erection.

Further, Chapter Eight clearly demonstrates the capabilities of the developed taxonomy to generate hierarchical and prototypical models that can be used multiple times to describe the operations involved in any steel structures erection. 3D models of the HRSG assemblies are developed and heavily used to investigate several HRSG design alternatives and identify improvement opportunities for on-site construction operations. Improvements are realized by initiating multiple parallel construction paths utilizing modularization, off-site prefabrication, and pre-assembly techniques.

In conclusion, this research introduces a new common taxonomy for modeling construction operations. This taxonomy applies a combination of techniques and knowledge from different areas to improve modeling and analysis of operations and consists of seven levels: product, assemblies and subassemblies, components, operations, processes, physics, and control. The hierarchical levels were established by exploring the ways construction field operations are carried out. Moreover, based on action research techniques, two practical case studies were developed in order to validate the capabilities of the common taxonomy. The order in which the taxonomy and the case studies were conducted provided the basis for conceiving the new modeling technique that is designed to usefully describe, capture, and analyze the diverse elements of construction operations.

This research confirmed the necessity for a common construction language so that improvements to complex construction operations and processes may be achieved. The examples introduced and examined have given us great confidence in the use of the developed taxonomy as a direct support language for enhancing the modeling of construction operations.

9.2 RECOMMENDATION FOR FUTURE RESEARCH

The research presented in this dissertation is only a step towards the creation of a common construction taxonomy that can be usefully used to model, capture and analyze construction operations. Since the developed taxonomy uses knowledge from many different areas, there is plenty of room for improvement and further work can proceed in many directions.

First, further enhancement to the developed taxonomy is an area with considerable research potential. The developed examples presented in Chapter 8 have shown that the developed taxonomy can successfully be used in modeling complex construction operations. However, further usability studies of the developed taxonomy are needed to realize its full potential in standardizing a structured construction modeling language. Further enhancement of the developed taxonomy could follow several paths.

1. Applying the developed taxonomy to broader range of construction operations to further validate its capabilities and to address the importance of its modeling structure. Chapter Eight presented two prototypes examples of construction applications that are related to the erection of steel structures. Additional

construction applications should be identified for further modeling and analysis such as, piping installation, cable pulling, etc.

2. Concentrating on certain levels within the developed taxonomy that may be considered for automation. For example, automate the modeling requirements at the process, physics and controls levels. Some of the processes and their related physical properties might be suitable for automation. For example, automate the required modeling processes to complete a MOVE operation for a steel member. Further investigation is required to identify the tasks or level that are suitable for automation. Furthermore, a controlled automation approach is required as well to maintain the integrity of the modeling system.

3. Integrating the developed taxonomy with product design processes during the various design stages is another research path. Chapter Seven introduced a framework that identifies areas of potential concurrency between the design process and developed taxonomy. A concurrent approach could explicitly draw in the considerations of construction, using advanced construction technologies or traditional methods, into the earliest design stages. The concurrent analysis of the design and construction of a product and the explicit of its subsequent construction operations may reveal new concepts that ease and improve the way we do construction today. Therefore, more in depth studies are required to concurrently integrate the design of products and processes at the various levels of the developed taxonomy.

A second research direction is to concentrate on the development of a construction computer-modeling environment that allows the development of construction operations models utilizing the developed taxonometric structure. This modeling environment is needed to further validate and test the flexibility and effectiveness of the developed taxonomy and to identify opportunities for improvements. This dissertation provides the basis and identifies a broad set of requirements that such modeling environment must posses in order to be successfully applied to modeling of construction operations:

1. The modeling environment should be a computer base system that uses an object-oriented programming language with the objective of providing a standard modeling environment that is based on the developed taxonomy and its structured construction language.

2. As discussed in Chapter Four and building on the review of previous works on computer modeling and simulation for construction, this research identifies virtual systems as the most promising modeling environments that have considerable potential in simulating complicated construction operations. Therefore a virtual environment for modeling construction operations is needed.

3. The user interface should support graphical representations and should be the primary mean of model development. The modeling environment should allow users to build models of construction operations in an intuitive and user-friendly manner. However, advanced users should still be able to access and develop extension tools to accommodate their modeling needs. Further investigations are needed to determine the guideline for developing a suitable user interface.

4. Since the developed taxonomy is hierarchical in nature, the architecture of this modeling environment should have a hierarchical structure as well.

5. The modeling environment must be able to exchange information with existing AEC applications in order to reduce the data entry requirements as well as to generate information for use by existing AEC applications. Therefore, further investigation of means for exchanging information within the AEC applications is needed. Chapter Seven identifies the industry foundation classes as the most promising building data models that have the potential to successfully provide the means for exchanging information with the AEC applications.

6. The modeling environment should support the use of prototype libraries to encourage the reusability of existing models. The objective of the prototype libraries is to serve as a general, reusable, and extensible tool that can be usefully used to construct models of construction objects and operations. Chapter Three introduces the concept of prototype libraries and its use for constructing physically-based models of graphical objects. Further research in how to construct and apply prototype libraries within the proposed environment is needed.

Third, the developed taxonomy was structured mainly to model and capture construction operations. Therefore, modeling the disassembly process of constructed facilities is another subject with considerable potential for a future research that could expand the scope of the developed taxonomy. Chapter Seven provided examples that show the potential use of the developed taxonomy to model the operations involved in the disassembly process of a steel structure. More in-depth evaluation of the disassembly processes is needed to understand what knowledge is important and how it can be modeled.

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VITA

Sami K. Al-Masalha was born in November of 1971 in the city of Zarka, Jordan. He lived there until August of 1989 where he graduated from Zarka high school. He then moved to Irbid, Jordan to attend Jordan University of Science and Technology (JUST) where he received a Bachelor of Science degree in Architectural Engineering in June of 1994. After teaching at JUST for a year, he traveled in August of 1995 to the United States to attend Virginia Polytechnic Institute and State University (Virginia Tech) where he received a Master of Architecture in May of 1997. In August of 1997, he joined the Department of Environmental Design and Planning at Virginia Tech where he successfully defended his dissertation on August 2, 2004 to receive a Doctor of Philosophy degree in Environmental Design and Planning. While pursuing his Ph.D., he also obtained a second Master of Science in Architecture with a major in Building Construction in May of 2000.