LIFECYCLE COST ANALYSIS FOR MODULAR DESIGN OF SOLAR POWER SYSTEMS

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LIFECYCLE LABOR COST ANALYSIS FOR MODULAR DESIGN OF SOLAR POWER SYSTEMS

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To humanity and its continuous improvement

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LIST OF SYMBOLS AND ABBREVIATIONS

BOS	Balance of System
SPRS	Solar Power Racking System
LCA	Life Cycle Assessment
DES	Discrete Event Simulation
IDEF	Integrated Definition
FEA	Finite Element Analysis

SUMMARY

Solar power systems are becoming increasingly popular due to the fact that solar power can offer time and money saving solutions for off-grid and grid-connected homes, cabins, and businesses with clean and affordable energy. However, there are still significant opportunities to reduce the cost of solar power systems by optimizing system design. This paper presents a methodology for evaluating the lifecycle labor costs of solar power systems. This methodology can help optimize system designs relative to cost. It can also support solar power system selection decisions based on a holistic lifecycle view. The methodology accomplishes this by first presenting a method to evaluate the modularity of competing systems, or design variants. It then describes a method of gathering data and modeling the systems so that it can be communicated to relevant stakeholders. Finally, it uses discrete event simulation to generate an estimate of relative lifecycle labor cost performance. Verification and validation of the methods described are presented through a case study of the MegaModule residential solar power system, designed by the team at GTRI. The paper concludes with a review of limitations and proposed future work.

CHAPTER 1

INTRODUCTION

This chapter provides an overview of the background research leading to this thesis. Discussion of the research motivation has led to the research problem being identified as the need to analyze the lifecycle costs of modular solar power systems. Subsequently research objectives and scope are developed in order to create a framework to accomplish this.

1.1. Background

Solar power systems have become more affordable in recent years because of advances in cell efficiencies and manufacturing technology. This has primarily reduced the cost of modules themselves, but there is still significant opportunity for cost reductions in the balance of systems (see Figure 1). The balance of systems includes everything that is required to integrate the module into a system that can generate power, which includes manufacturing, framing, racking, wiring, labor and maintenance. However, these activities are complex and vary based on the type and application of the system.

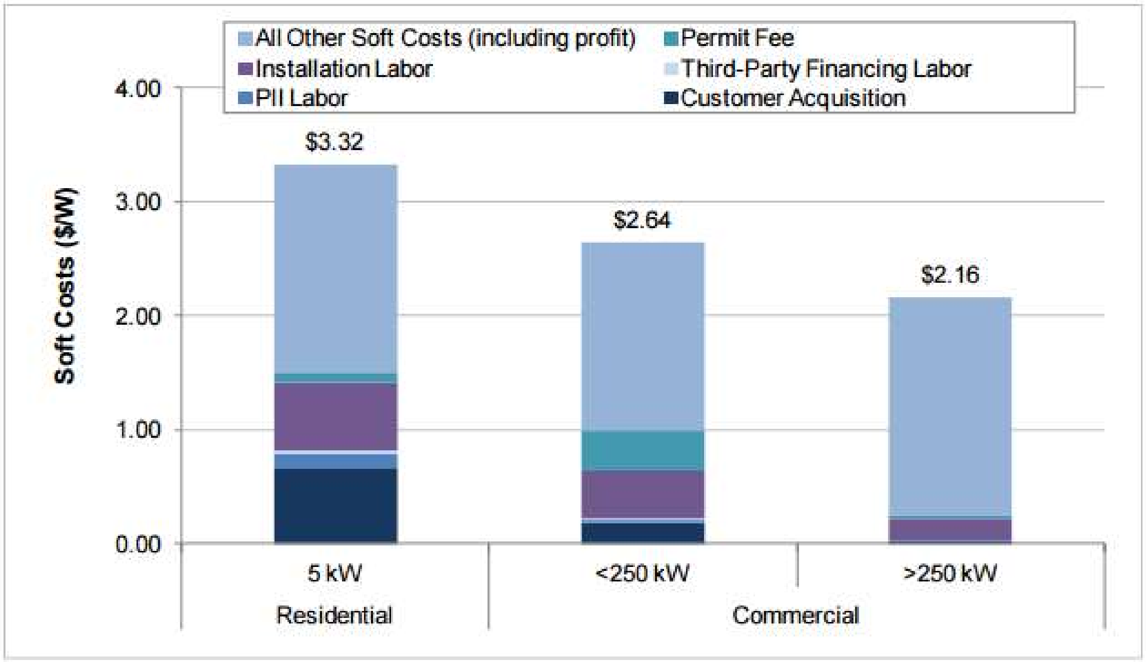


Figure 1.1.1.1 Solar System soft costs[1]

Figure 1.1.1 shows the level of soft costs in solar power systems. Labor costs for all types of systems are the second largest source of non-hardware costs. As a result it has been recognized by the solar power community that it is a significant opportunity for cost reduction. While installation may have the greatest categorical cost visibility because of its labor intensive nature, costs throughout the solar system lifecycle can be reduced through improved design. This paper seeks to propose a framework that will support the design of solar power systems with the lowest lifecycle cost.

1.1.1. Typical Solar Power System configuration

A typical solar power system consists of modules to generate power from solar radiation and balance of systems that include an electrical system, a structural system and the business processes. The BOS is typically considered to be the system exclusive of the actually panels themselves. BOS costs can be further broken down into costs associated with inverter, wiring, racking, site prep, etc. BOS costs currently comprise half the system costs, with the other half going towards the modules themselves.

Modules are typically considered separately since they come shipped as a fully assemble unit from the manufacturer. Each module typically consists of a frame, laminate and junction box. The laminate configuration is dependent on whether the module is mono or poly crystalline, or amorphous silicon. The difference between these is the medium used to convert solar radiation to electrical power. However, regardless of the medium, the laminates typically consist of a layer of glass, encapsulant, conversion medium, copper interconnects and ribbons, and backsheet, laminated together. The frame adds stiffness to the structure and prevents excessive deflection of the module system. The junction box is used to transition from the ribbons to outdoor rated wire. Modules wires are usually connected together in series to form strings.

1.1.2. Balance of System (BOS)

The connection of modules into strings begins the BOS. The electrical BOS is responsible for the transmission of generated power from the modules to the intended application. The conversion from solar radiation to electrical energy produces DC power which is typically used to charge batteries, via a charge controller. Most commonly however, the DC power is converted to AC power since most consumers use AC. The conversion of DC to AC is achieved through an inverter. Once converted, the power can be used directly or fed into the grid. In the cost context, the electrical system consists of all the components that deal with the transmission of power. This includes wiring, inverters, batteries, etc.

The structural system is responsible for the protection of the electrical system. It consists of the racking system that holds modules in place, the conduits and harness that are used to route and protect wiring, and the various structures that enclose equipment such as inverters and batteries. The most important of these is the racking, which is also the largest cost component. The racking must be able to withstand wind and snow loads, and prevent the system from flying away due to uplift. The racking system is also the interface between the electrical system and the application substrate. For example, some racking systems are designed to attach modules to roof structures, while others attach them to the ground in facility type applications.

Business processes include those that facilitate the procurement, construction and operation of the solar power system. Procurement processes include the costs to acquire a customer, make a sale, configure a system, and schedule an install. Construction business costs include the scheduling, permitting, etc. that are required to construct the system for a particular customer. Operation costs may include the cost of connecting to the grid, or selling the power generated.

1.1.3. Cost Reduction Efforts in BOS

The Sunshot initiative was created to drive down the cost of solar power so that it can be competitive with conventional power sources[2]. To do this the DOE awarded research grants to look at ways to reduce the cost of solar material, manufacturing, installation and maintenance. One such award focused on the reduction of BOS costs through research on BOS design, manufacturing, assembly and installation. The SIMPLE Bos project was thus formed to drive down the cost of the BOS.

The cost of the BOS system stems from the materials, processes, transportation and labor that result in the deployment of a system. Material costs arise from the material used to make the various components. Process costs include the costs of fabrication, assembly, finishing, etc. Transportation costs can include costs to transport the systems and components to an application site. Labor costs include the man hours spent manufacturing, installing and maintaining the system. All of these categories of costs vary depending on the system type, application, and manufacturer or installer.

Labor costs in particular are the most challenging to determine. Activity based costing is not well established in the nascent solar industry and often leads to inefficiencies in the allocation of labor cost. Additionally, there is a high variability between individuals performing the same activities. Through proper design labor costs in the BOS can be reduced, but they must first be identified and studied. Studying these costs will also provide insight into the degree of variability and provide opportunities for labor cost reduction.

1.1.4. Solar Power Racking Systems

Racking systems in particular form the interface between the modules and a structurally stable substrate. According to Figure 1.1.1. , racking is the largest cost contributor to the structural costs of the BOS. Additionally, the design of the SPRS has a significant impact on the site prep, attachments and installation cost components. As a result they provide a tremendous opportunity for BOS cost reduction. The SPRS will be the portion of the solar power system considered in this paper since its lifecycle is representative of the entire solar power system lifecycle.

1.2. Research Objectives and Scope

Fundamental to the reduction effort is the need to understand the implication of design decisions on lifecycle labor costs. This is extremely relevant to the solar power industry, which is attempting to attain grid parity, but has reached a saturation point with respect to efficiency increases and must now focus on balance of system costs. This thesis seeks to propose a framework, which can be used to evaluate lifecycle cost implications through relative evaluations of solar power system designs. This framework can help researchers and solar power system designers to evaluate various systems and also iterate their designs to the most cost effective solution. It can also help solar power distributers and consumers to evaluate competing products and make a selection based on long term cost competitiveness.

Modularity is believed to be a key differentiator between systems and can affect many aspects of system design, performance and cost. There are several methods to evaluate modularity and this framework will propose a method. In doing so it will provide a measureable difference between competing designs. This is important since there is often a sweet spot where a certain degree of modularity minimizes lifecycle cost. Designers, researchers, distributers and consumers will be able to measure the modularity of their system in various permutations and configurations and tie it to a cost. They will then be able to increase or decrease modularity so as to reduce lifecycle labor cost.

Another area of inquiry relevant to the research question is the characterization of the lifecycle of a solar power system and its modeling. It is important to understand the delineation of the various stages in the lifecycle so as to compartmentalize the analysis parameters. For example, activity time durations may provide a basis for separation as activities during the manufacturing stage take place within minutes, during the installation stage within hours, and during the maintenance stages during years. Modeling of this characterization must be able to support the further levels of analysis that need to be performed, and at the same time support communication between various stakeholders. This is extremely important as the design, data gathering and evaluation process requires the participation of various skill sets each with its own ontology of description. A standardized modeling methodology is necessary to provide a method of describing the lifecycle characterization and activities across the various skill domains.

A final area of inquiry is the method of analyzing costs over the lifecycle and in situations for which significant data is not available. This is important for two reasons. The first is because one of the intents of the research question is to evaluate conceptual designs that do not have much actual usage data. The second is the high degree of variance in activities which makes it difficult to deterministically analyze system costs.

Once the framework has been developed a case study will be used to verify and validate it. This will utilize solar system designs and data from the GTRI research project. The results of the case study will be analyzed to derive conclusions about the competing systems. The paper will then conclude with identification of deficiencies and proposals for future work that can improve the process of analyzing solar power system labor cost.

1.3. Organization of this Thesis

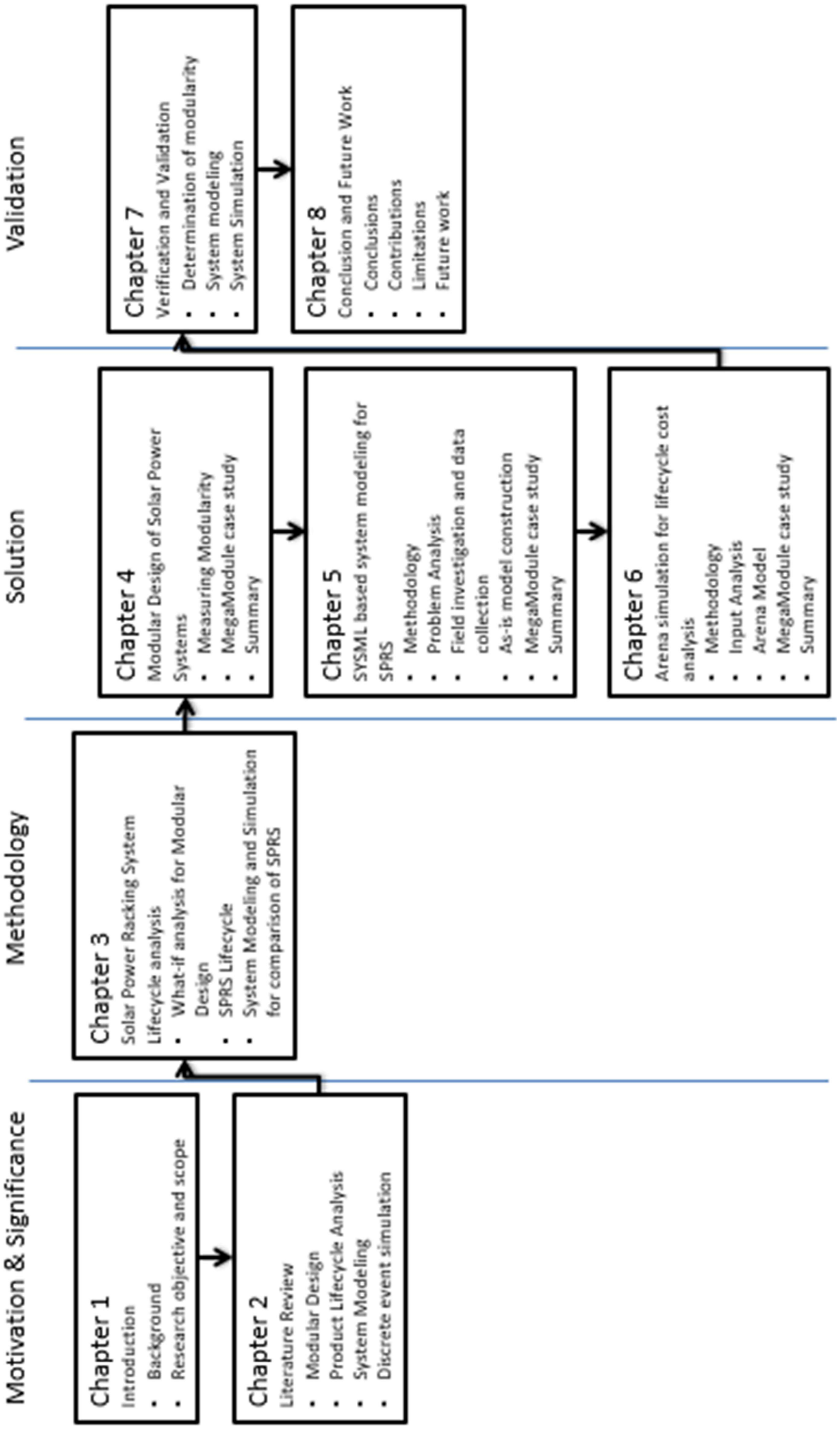


Figure 1.3.1 Diagram illustrating thesis coherence and flow

1.3.1. Motivation and Significance

This chapter established the motivation for this paper. There is a need to reduce cost within the solar power industry. In short, the research question asks how solar power systems can be analyzed for lifetime cost at the design or selection stage. Soft costs in the BOS are one area that this question is particularly relevant and can be targeted with good design and engineering to reduce cost. However the evaluation of this impact is difficult because the activities that contribute to soft cost are difficult to model deterministically, and occur throughout the 25 year lifespan of a solar power system. Using modularity as a differentiating feature, using abstraction as a method of communicating design intent, and using modeling and simulation, this paper proposes a framework to fulfill this need.

Chapter 2 will look at existing literature in the areas of modularity, lifecycle analysis, system modeling and discrete event simulation. This literature review will provide a state of the art foundation for the proposed framework. In particular it will inform the need for modularity and its measurement. It will present existing lifecycle paradigms to build from, such as the LCA methodologies used in sustainable design. A review will be conducted of the IDEF and SysML modeling method to capture the design in standardized form that can be communicated across different competencies. It will finally look at uses of discrete event simulation to evaluate costs in various other scenarios, and present the use of ARENA as a tool to conduct the simulation.

1.3.2. Methodology

Chapter 3 will present and discuss the areas of enquiry that will help answer the research question. The research question necessitates 3 areas of inquiry. The first area of inquiry is a method of differentiating between systems using some holistic measure. Chapter 3 will present Modularity as one such measure and can provide the differentiating factor for what if analysis of different systems and configurations. A second area of inquiry is the paradigm of the lifecycle stages. Chapter 3 will discuss the technical challenges associated with characterizing the lifecycle of solar power systems and using lifecycle stages as a basis for comparison. Finally, a third area of enquiry is the use of modeling and simulation to analyze lifecycle cost. Chapter 3 will discuss the challenges this presents, such as high variability of activities and their duration.

1.3.3. Solution

This section presents the solution to the challenges identified by the three areas of inquiry in the previous section. In each of these chapters an application to the case study is provided as verification and validation.

Chapter 4 in this section presents a method of evaluating the modularity of systems. The crux of the method lies in the evaluation of functional and structural similarity, which is then used to calculate a holistic modularity measure. The chapter then describes the application of this method to a case study to demonstrate its use.

Chapter 5 describes the use of SysML to model the system. It describes the major lifecycle stages as manufacturing, installation and maintenance. Further it provides a methodology leading to the SysML modeling, which includes problem analysis, field investigation, and data collection. The application of this methodology to the case study is then described, resulting in SysML models for the case study solar power systems.

Chapter 6 delves into the stochastic modeling of the system costs. A detailed description of the input analysis method is provided, which facilitates the use of standardized distributions within the ARENA simulation system. Finally, the method of model construction and simulation within ARENA is presented and described. The section ends with a description of input analysis and simulation as applied to the case study.

1.3.4. Conclusion & Future work

This final section presents the conclusion to the research question and the three relevant inquiries. It briefly discusses each area of inquiry, the solution proposed and the application to the case study. Further, this chapter discusses relevant contributions to the development of the methodology, its limitations and future work. .

CHAPTER 2

LITERATURE REVIEW

Modular design, product lifecycle analysis, system modeling and discrete even simulation are well developed in academic literature. This chapter seeks to review current research in these areas with the goal of creating a firm foundation upon which to meet the research objectives. This foundation also provides the motivation to pursue research in the lifecycle analysis of solar power systems. Major challenges and future research directions are also discussed.

2.1. Modular Design

In product development, “modules of subcomponents or sub-assemblies are interchangeable in ways that can produce a variety of products” [3], to satisfy customized combinations of needs. Modularity can also extend to functional units which when combined can accomplish overall part or product functions. The attribute of modularity itself can be explained as “the extent of purposeful structuring of the product architecture for identification of independent, standardized or interchangeable units to satisfy diverse functions”[4]. This attribute can provide significant benefits and many researchers have discussed these in great detail. Benefits of Modularity include economies of scale, increased flexibility of product component change, increased product variety, reduced order lead time, decoupled risks, and easier product diagnosis, repair and maintenance.

2.1.1. Modularity Benefits

Many of these benefits derive from the interchangeability resulting from modular design. Interchangeability gives designers flexibility to meet changing requirements, allows delaying decisions until more information is available without delaying the development process, and reduces lifecycle costs by reducing the number and repetitiveness of processes [5]. Sosale et al.[6] discussed the two main benefits of interchangeability with respect to product functionality; reconfiguration allows the product to fulfill additional required functions, and customization can provide customers with a choice of modules. With respect to production, Erixon et al.[7] showed that increased interchangeability has “positive effects on information and material flow within a company”, due to the avoidance of redundant development efforts and an increase in standardization. As a result of these and the effects of interchangeability on maintenance and disposal, Newcomb et al.[8] propose that modularity leads to “decreased cost over the lifecycle”.

Modularity enables two fundamental cost reduction mechanisms during manufacturing; “Learning curve effect, and parts and material price breaks”[5]. Since modularity creates variety through combinations of fewer types of assemblies, production of each assembly will increase. As a result production process knowledge for each of these assemblies will also increase as operators spend a larger amount of production hours on each assembly. This eventually leads to innovations in process design that can streamline the production process; similar to the economies of scales effects of mass production. Economies of scale also apply to vendor supplied components. Parts and material price breaks increase due to procurement of larger quantities of required parts from vendors. Higher production of a specific assembly module results in higher quantities of parts procured for that module. Vendor discounts for higher part quantities are very common in industrial practice.

2.1.2. Implications for Product Lifecycle

Modularity has implications for product lifecycle through its impact on design, manufacturing, assembly, installation, distribution, operation, reuse, re-manufacturing, recycling and disposal [9]. Modularity objectives within each of these are often in conflict, and therefore require compromises to enable net benefit. In general, modularity objectives for product life cycle include dividing design task for parallel development, production and assembly improvement, increased standardization, increased serviceability, reduce time to market for new products, enable reconfiguration for multiple applications, improve end of life treatment, and increase product variety[9]. These objectives are also the primary benefits of modularity with respect to the product life cycle.

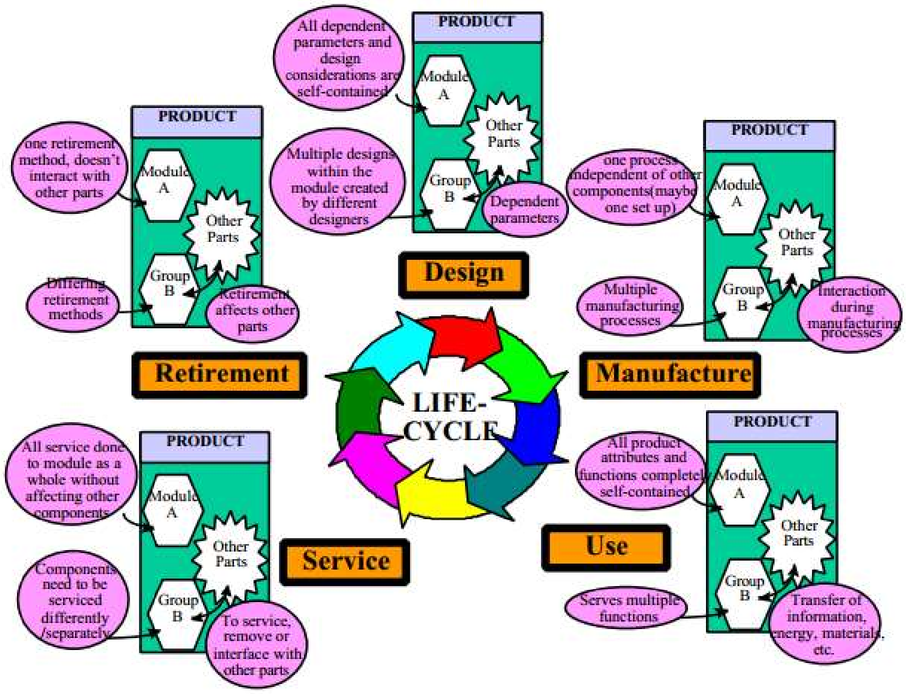


Figure 2.1.2.1 Views of a product as it goes through some of the major life-cycle processes. Module A is Modular, Group B and other parts are non-Modular [10]

2.1.3. Degree of Modularity

The objective of modular design is to group related components into modules that exhibit higher similarity in function and structure. This degree of modularity can be considered a descriptive characteristic of different compositions of components. However, since modularity is derived from function and structure, it can also have implications to cost, material use, etc. Therefore modularity is a descriptive characteristic with effects in multiple domains of significance. As a result, being able to determine this characteristic has several benefits as it supports determination of modularity effects in domains such as total labor cost, which is the domain of interest for this paper.

2.2. Product Lifecycle Analysis

Products of all kinds go through several stages of life that form their lifecycle. The ontology of a lifecycle may vary by type of product and the impetus for the creation of a lifecycle description. In general, most lifecycles consist of a distinct beginning, a period of use and an end. The beginning may be set at when the product is conceived as a concept, or when the raw materials are staged for its production. The period of use is the stage during which the product fulfills its intended purpose. This may begin when a customer buys the product, or when it fulfills its function for the first time. Finally, the stage at which it ceases to fulfill its intended function may be designated its end of life. At the end of its life the product may be recycled, scraped or repurposed. Most of the time product value is maximized by transferring the material and technological value to other product lifecycle streams.

In the modern product development environment, it has become increasingly important to design products with their entire lifecycle in mind, and not just their intended function. Benefits of this holistic view can be seen in increased reliability, customer satisfaction, and sustainability. In particular, the levelized value of the product can be lowered. Inherent in this is the reduction of raw material consumption and production energy. This is the main premise behind the Life Cycle Assessment (LCA).

2.2.1 Life Cycle Assessment

LCA is a methodology used to assess the environmental impacts of a product at every stage of its lifecycle. Typically, a product's lifecycle begins at material inputs to the manufacturing process and ends at disposal. Intermediate steps can include production processes, use, maintenance, upgrades, and reuse; **Error! Reference source not found.** shows generic life cycle. As a result of this lifecycle perspective, the LCA methodology provides a holistic outlook on a products existence. This outlook facilitates robust comparisons between products for purposes of product design selection, public policy, consumer choice, marketing, etc. Most importantly it facilitates selection and development of products that have a lower net negative impact on the environment. The procedures through which this impact is assessed are part of the ISO 14000 environmental management standards.

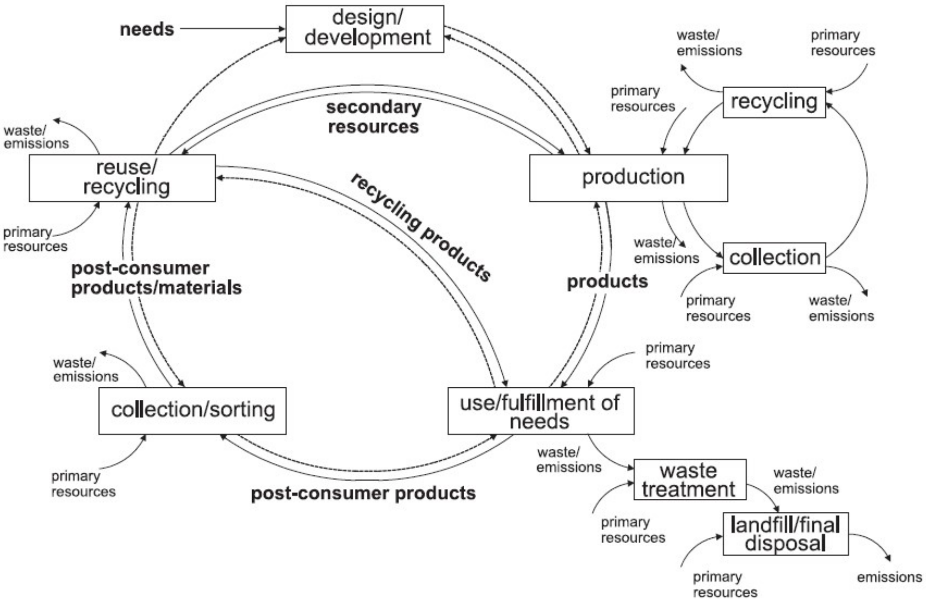


Figure 2.2.1.1. Schematic representation of a generic lifecycle [11]

A LCA has four main phases. It begins with a goal and scope which sets the context and customer for the study. Inventory Analysis follows and involves analyzing flows of material, energy, signals, etc. two and from nature and the product system. The third stage in the sequence, the Impact assessment stage, evaluates the significance of potential environmental impacts based on the inventory analysis performed earlier. The Interpretation stage is the final stage, and it ties together the results of the activities performed in the first three stages. As with many assessment methodologies, each phase is highly interdependent and iterative. The results of the interpretation stage are typically used in various applications, such as evaluating alternative designs for lowest environmental impact.

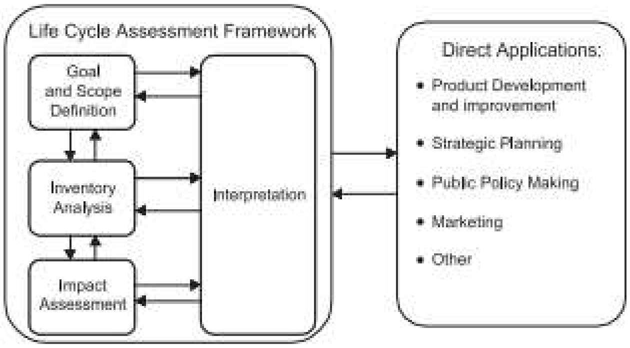


Figure 2.2.1.2 Phases of an LCA based on ISO 14040 [12]

2.2.2. Life Cycle Cost

The competitiveness of a product is primarily a function of its quality, cost and time to market. It has been recognized that optimization of cost and time to market requires a lifecycle engineering and design approach [13]. In fact, time to market is often factored into the cost of the product itself. Most papers on product lifecycles distinguish between design, development, production, use, and disposal. As a result, many of the optimization activities involve analysis and modification of cost issues in “lifecycle design” [13], “production and construction cost” [13], “operation and support cost” [13] and “retirement and disposal cost” [13]. A primary component of the analysis activities is the estimation of cost. There are many approaches to obtaining estimation, and these include methodological and modeling approaches. Some of these will be discussed.

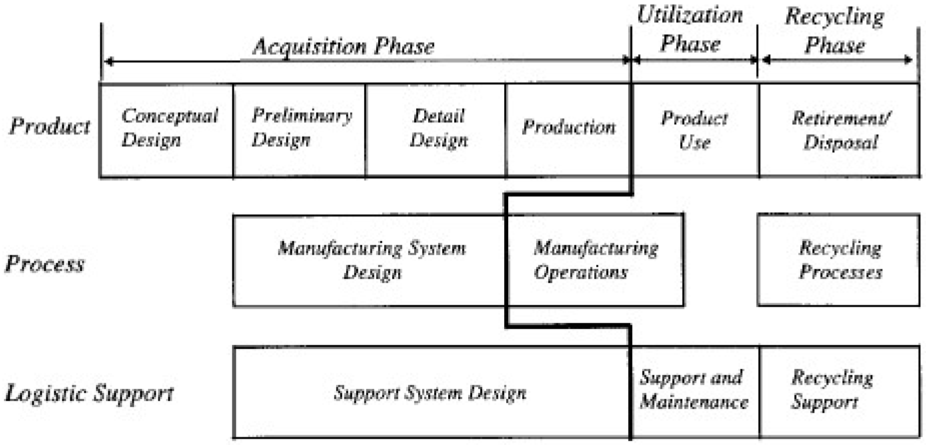


Figure 2.2.2.1 Parallel lifecycles in product development [13]

Cost estimation is essential to decision making at the design stage. Since the designer has to evaluate several concepts to fulfill functional requirements, cost estimation of concept variants can provide relative measures of cost efficiency and aid selection. These estimates of cost are uncertain but need to be given due consideration because most of the lifecycle cost (between 70-85%) is committed to at the design stage[13]. To facilitate cost estimation, industry has developed several estimation models. These can be broadly categorized as “parametric models, analogous models, and detailed models” [13]. Each of these varies in effort required and accuracy of estimation as well as applicability to product domains. Brief descriptions of each are summarized below.

2.2.2.1. Parametric Models

Such models utilize equations that describe relationships between “cost schedules and measureable attributes of a system” [13, 14]. The benefits of such models is that they can provide correlations between various aspects of the systems, such as the relation between building cost and floor area [13]. However, these models can require significant effort since they require a “systematic collection and revision process to keep the” [13] various equations updated. Another downside is that it is difficult to estimate the impact of new technologies since cost data is often not available.

2.2.2.2. Analogous Models

Use of analogous products or components is characteristic of this model. To estimate the cost of the target product, the analogous subject model is adjusted for cost differences between it and the target product [13, 15]. Effectiveness of this model is a function of the ability to correctly identify the differences between the target and analogous case [13, 16]. Expert judgment and familiarity with the product and process are required to identify and deal with similarities and make adjustments for perceived differences. “This approach though tends to be very good for new products” [13].

2.2.2.3. Detailed Models

“A detailed model uses estimates of labor time and rates and also material quantities and prices to estimate the direct costs of a product or activity” [13, 15]. Allocation rates are used to allow for indirect/overhead costs[13]. “This is known as bottom-up estimating and is widely used by organizations to build up estimates from task or work-package level” [13, 16]. This approach is analogous to activity based accounting in that costs are determined through the product of hourly rates and the time taken to complete a task[13]. This approach is flexible and can the data gathered can be easily adapted and reused for a variety of products. However the downside is that there is significant effort required to collect, manage and update information. This is therefore the most time consuming and costly approach.

It is essential that cost estimates be as close to realistic as possible. The Frieman Curve shown in Figure illustrates the implications of over or under estimating cost. Underestimation of cost leads to increased expense in reorganization, re planning and possible addition of personnel and equipment [17]. On the other hand, when costs are overestimated, rather than resulting in greater profits, the overestimate reflects a "Parkinson' s law application: the money is available, it must be spent" [17]. Unfortunately, accuracy varies with phase of development. "In the early phases when information is scarce, cost estimates can have a - 30 to +50% accuracy"[18]. "By the detailed design stage it should be within - 5 to +15%"[18].

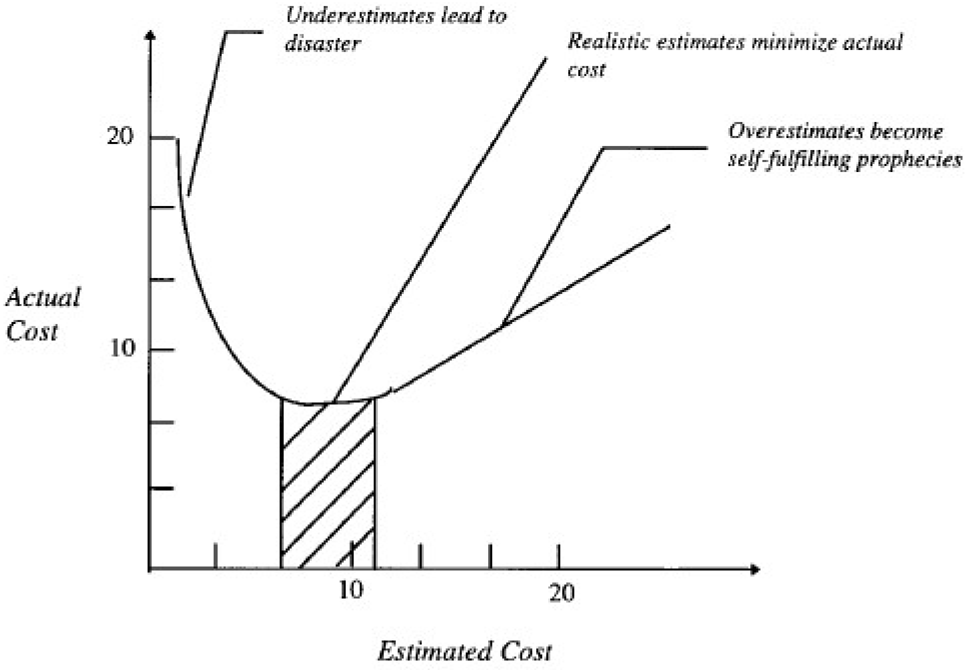


Figure 2.2.2.2 Frieman Curve [17]

Service model analysis (SMA) [19] "is an evaluation method for design for serviceability" [13] and can fit into a lifecycle cost analysis. In their paper, Asiedu et al. [13] describe service categories as service modes. These service modes include "regular maintenance, repair of failed components of systems, or service for undesirable side effects"[13]. One implementation of SMA utilizes a computer algorithm to infer the sequence of steps needed for each mode of service. The "labor step cost (LSC)" [13] is then calculated using equation 2.2.2.1 [13].

$$LSC = (t_1 + p_1) \times c_{ir} + (c_p + p_p) \qquad 2.2.2.1\ [13]$$

where

t_l is the labor time

p_l is the labor time penalty

c_{ir} is the labor rate

c_p is the part or material cost

p_p is the part or material cost penalty

The LSC computes the labor cost at a given. Step. Lifetime labor costs are a function of the step costs and the frequency at which they occur[13]. Asiedu et al[13] propose an algorithm to calculate the lifecycle cost using Equation 2.2.2.2[13].

$$LCSC = \sum_{k=1}^{n}\left[\sum_{j=1}^{m}\left(f_{R_{j,k}}\sum_{j=1}^{m} LS\ \ _{i,j}\right)\right] \qquad 2.2.2.2[13]$$

where

$f_{R_{j,k}}$ is the frequency of labor operation j associated with service mode phenomenon k

$LSC_{i,j}$ is the labor step cost i associated with labor operation j

l is the number of labor steps associated with labor operation j

m is the number of labor operations associated with service mode phenomenon k

n is the number of service mode phenomenon being evaluated

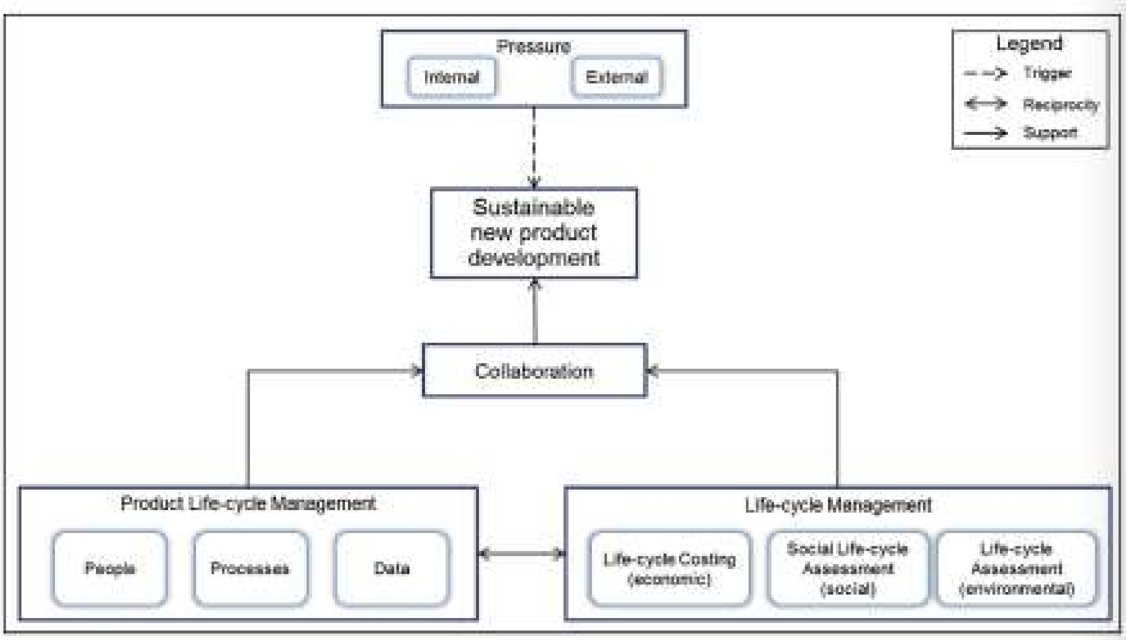


Figure 2.2.2.3 A framework of a life-cycle focused sustainable new product development [20]

2.2.3. Levelized cost of electricity

"Levelized cost of electricity (LCOE) is the constant dollar electricity price that would be required over the life of the plant to cover all operating expenses, payment of debt and accrued interest on initial project expenses, and the payment of an acceptable return to investors" [21]. The LCOE methodology is an abstraction from reality and is used as a benchmarking or ranking tool to assess the cost-effectiveness of different energy generation technologies[22]. The method usually does not include risks and different actual financing methods available for the different technologies [23]. "Recognizing that LCOE is a benchmarking tool, there is high sensitivity to the assumptions made, especially when extrapolated several years into the future"[24]. "Ordinarily, LCOE is a static measure that looks at a snapshot in deriving the price per generated energy, while true markets prices are dynamic"[24]. "In general, estimates for LCOE for solar PV tend to be fairly high compared to alternatives based on common assumptions"[24]. Equation 2.2.3.1. is one method that can be used to calculate the LCOE [24].

$$LCOE = \frac{\sum_{t=0}^{T}(I_t+O_t+M_t+F_t)/(1+r)^t}{\sum_{t=0}^{T}S_t(1-d)^t/(1+r)^t} \qquad 2.2.3.1.\ [24]$$

where,

I_t is the initial investment/cost of the system including construction, installation, etc., in $

T is the life of the project in years

t is the year t

M_t is the maintenance costs of the system in for t years in $

O_t is the operation costs for t years in $

F_t is the interest expenditures for t in $

r is the discount rate for t in %

S_t is the yearly rated energy output for t in kWh/year

d is the degradation rate in %

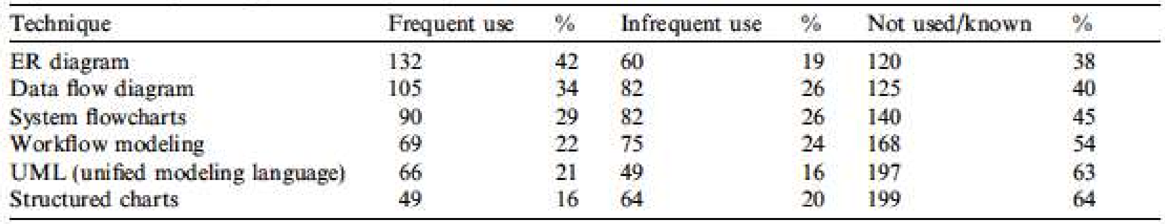
2.3. System Modeling & Analysis

Processes in an organization can be categorized into "material processes, information processes, and business processes"[25]. Material processes are considered to be all those that "assemble physical components and deliver physical products"[25]. These processes include "moving, storing, transforming, measuring" [25], etc. "Information processes relate to automated tasks and partially automated tasks" [25] performed by or through interaction with a computer. Database systems tasks are an example of this[25]. Business processes are "market centered" [25] and can be "implemented as material or information processes" [25]. These categorizations attempt to capture the diversity of tasks in an organization. In the modern world, a competitive organization must be able to gain economies of integration through the efficient interaction of these processes. Process modeling is one way to enable economies of integration.

The roots of process modeling can be traced back to the early 20th century as a tool for organizational design. Achieving economies of integration, which can be considered a component of “sustainability in manufacturing requires a holistic view spanning not just the product, and the manufacturing processes involved in its fabrication, but also the entire supply chain, including the manufacturing systems across multiple product life-cycles” [26]. Modeling tools and process fulfill a need to integrate systems like IT and enterprise; provide ‘‘organizational glue’’ that binds “strategic, tactical and operational activities carried out within and between organizations” [27].

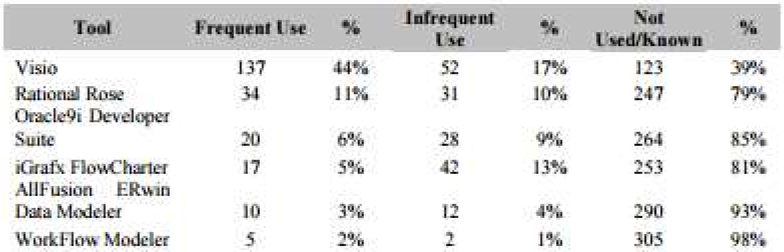
However, the type of tool and use varies by company and reliance on such tools is often determined by the size of the organization. One study investigated the use of different tools and the size of the organizations that use them. It was discovered that modeling technique use was found to decrease significantly from smaller to medium-sized organizations, but then to increase significantly in larger organizations (proxying for large, complex projects[28]. This “study also found that found that the top six most frequently used modeling techniques and methods were ER diagramming, data flow diagramming, systems flowcharting, workflow modeling, UML, and structured charts” [28].

Table 2.3.1 Usage frequency of different diagramming techniques [28]



Technique	Frequent use	%	Infrequent use	%	Not used/known	%
ER diagram	132	42	60	19	120	38
Data flow diagram	105	34	82	26	125	40
System flowcharts	90	29	82	26	140	45
Workflow modeling	69	22	75	24	168	54
UML (unified modeling language)	66	21	49	16	197	63
Structured charts	49	16	64	20	199	64

Table 2.3.2 Usage frequency of different modeling tools [28]



Tool	Frequent Use	%	Infrequent Use	%	Not Used/Known	%
Visio	137	44%	52	17%	123	39%
Rational Rose	34	11%	31	10%	247	79%
Oracle9i Developer Suite	20	6%	28	9%	264	85%
iGrafx FlowCharter	17	5%	42	13%	253	81%
AllFusion ERwin Data Modeler	10	3%	12	4%	290	93%
WorkFlow Modeler	5	2%	2	1%	305	98%

2.3.1. Guidelines for Modeling Method

Mendling et al.[29] have identified 7 guidelines to help build a process model from scratch as well as for improving existing process models. These guidelines are based on empirical research that takes into consideration process model understanding, error probability of process model, ambiguity of activity labels. The 7 guidelines from their paper are briefly described below:

G1: “**Use as few elements in the model as possible”** [29]. Error increases with the size of a model[29].

G2: “**Minimize the routing paths per element”** [29]. Routing paths to and from an element determine its degree. There is a strong correlation between the number of modeling errors and the average or maximum degree of elements in a model[29].

G3:” **Use one start and one end event”** [29]. “Number of start and end events is positively connected with an increase in error probability” [29], and “models satisfying this requirement are easier to understand and allow for all kinds or analysis (e.g., soundness checks)” [29].

G4:” **Model as structured as possible”** [29]. “Split connectors must be balanced by join connectors, similar to how open brackets must have an equal number of closed brackets in an equation” [29]. This makes the model structured. “Unstructured models are not only more likely to include errors, people also tend to understand them less easily”[29].

G5:” **Avoid OR routing elements”** [29]. “Models that have only AND and XOR connectors are less error-prone”[29].

G6:” **Use verb-object activity labels”** [29]. There are two major categories of labeling styles, Verb-Object (such as “inform complainant”) and “Action-Noun” (such as” complaint analysis”) [29]. The former has been found to be much less ambiguous[29].

G7: “**Decompose the model if it has more than 50 elements”** [29]. “For models with more than 50 elements the error probability tends to be higher than 50%”[29].

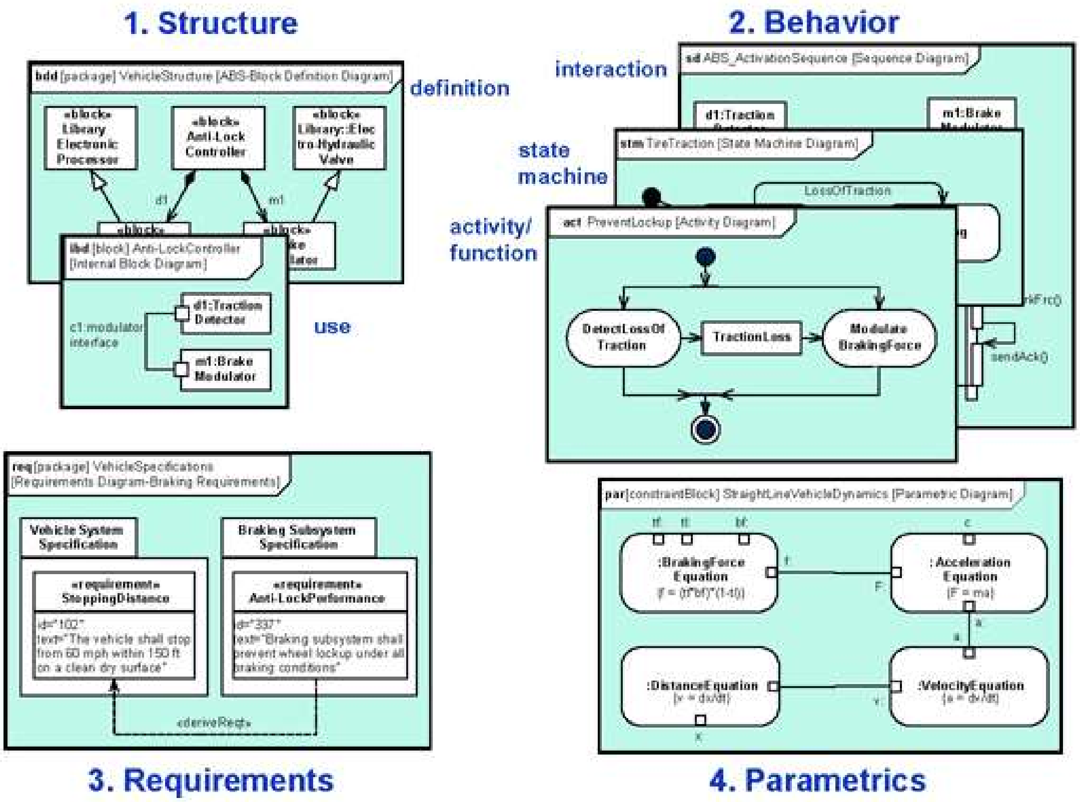
2.3.2. IDEF

The IDEF suite of enterprise modeling approaches have been applied extensively in support of large industrial engineering projects [27]. It is one type of graphically based modelling technique that helps tie together the variety of process domains that exist in a large organization. To facilitate a wide range of uses, IDEF consists of 14 variants identified by IDEFx, where x is the variant number. IDEF0-4 were developed in full by 1995[30] and support function modeling, information modeling, data modeling (IDEF1X), simulation modeling, process description capture, and object oriented design, respectively. IDEF5 was developed later and is used in multiple domains to capture a variety of ontological information.

A common ontology is important when contributors to common goal come from diverse backgrounds. IDEF5 provides this capability by allowing participants to capture domain knowledge in a form that can be understood by all. For example, Kun et al.[31] used IDEF5 to capture knowledge about product development, and to serve as a foundation for knowledge management in collaborative product development. Tsou et al. [32] used IDEF5 to develop the ontology of a supply chain model and compared it with one developed in Ontolingua. This activity showed that the use of IDEF5 did not compromise the original nature of the model and compared well with the Ontolingua description.

2.3.4. SysML

SysML is a subset and extension of the Unified Modeling Language. Figure 2.3.4.1 illustrates the differences between SysML and UML in terms of the diagram types available. In terms of application, SysML is considered to be more expressive and flexible and easier to learn than UML. Primarily, it is easier to apply to non-software related applications, such as manufacturing processes, or supply chains. Like UML it facilitates a standardized and intelligent method of capturing system knowledge, and includes features that provide parametric connectivity between elements. Recently, it has become the preferred method of modeling large complex systems, which require multiple domains to work together.



Note that the Package and Use Case diagrams are not shown in this example, but are respectively part of the structure and behavior pillars

Figure 2.3.4.1 SysML Diagram Types /the 4 pillars of SysML [33]

SysML can be used in many important activities during the system life cycle including communication with Stakeholders, improving system knowledge, model execution and verification, and documentation for maintenance[34]. The four diagram types, or pillars, of SysML that support these applications are Structure, Behavior, Requirements, and Parametrics, and are illustrated in Figure 2.3.4.1.

2.4. Simulation Analysis and Simulation Technique

"Discrete event simulation concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time" [35]. DES has several real world applications that require the modeling and estimation of stochastic processes. Healthcare has been an area where this has been used extensively, and Jun et al. [36]present one such case study. Its use in industry is extensive, and tools like Arena, Simio, etc. have made it very easy for novices to be trained in the method.

DES has been used in many instances to evaluate costs of systems with uncertainty. For example, Spedding and Sun [37] applied discrete event simulation to the costs of activity-based manufacturing systems. They concluded that it provided similar results as those derived from an IDEF (Integration DEFinition) modeling approach, but had the added advantage of being able to provide greater detail and take into account the intrinsic variation of a manufacturing system[37]. Martin [38] used discrete event simulation to create a flexible model to simulate the lifecycle costs of defense systems. The model applied concepts of operations, maintenance strategies, and reliabilities to determine lifecycle events, such as consumables and maintenance operations performed on the system through its lifetime[38]. It then determined the distribution of operations and maintenance costs, which is a result of the uncertainties of each lifecycle event[38].

Use of discrete event simulation to compare alternative design concepts is not new. Hayes [39] created a simulation based framework to compare alternative designs of a tactical naval Command and Control system. Arena simulations were conducted for the proposed and alternative concepts, and the results were compared to demonstrate the feasibility of the framework. Alix and Zacharewicz [40] used discrete event simulation to compare product-oriented and use-oriented product service systems. The simulation results provided decision guidance to support the choice of one scenario over another[40].

There are several methods of performing discrete event simulation. One of the most common methods is a simulation program. Arena [41]is extensively used in industry to perform discrete event simulations. It was developed by Systems Modeling and then acquired by Rockwell automation in 2000. Due to its ubiquitous use, there are several textbooks and user guides that incorporate the teaching of discrete event simulation with the use of Arena. As a result, this will be the preferred DES software for this paper.

2.5. Summary

This section explored the state of the art literature in the areas of modular design, product lifecycle analysis and system modeling and analysis. Modular design was shown to be beneficial to system design in general. However there is a sweet spot beyond which the system experiences diminishing returns. LCA methodology was reviewed as it is currently extensively used to conduct lifecycle analysis for the purposes of sustainability. The process of conducting LCA has four main stages; goal and scope, inventory analysis, impact assessment, and finally interpretation. Finally the section reviewed Modeling and Simulation. It discussed systems modeling as way to achieve economies of integration. The use of modeling by different sizes of organizations, and the variation in the types of tools used was also discussed. Further, a list of the most common types of modeling tools was presented. IDEF modeling was also introduced as a modeling standard to standardize modeling. To make the modeling process more intelligent, SysML was introduced and discussed. Finally a review of discrete event simulation for cost estimation and system comparison was conducted, and a brief description of Arena was presented.

CHAPTER 3

SOLAR POWER SYSTEM LIFECYCLE COST ANALYSIS

Solar power systems are inherently modular due to high variability of application conditions. In general, a solar power system consists of an energy collection system, a system to hold and orient the collection system, a system to transfer the collected energy, and a system to convert that energy into a usable form. For example, a typical solar power system consists of a system of solar photovoltaic panels as the collection system, a racking system to hold and orient the panel system, a wire and wire management system to transfer collected energy, and an inverter or a system of inverters to convert the generated dc power into usable ac power. The solar photovoltaic collection system is made up of photovoltaic modules that are strung together in specific configurations to build up an appropriate system voltage.

The following sections will consider the solar power racking system. This system typically serves as the system that holds and orients the collection system. It will be shown that there is significant opportunity to reduce the overall system cost labor cost by analyzing the lifecycle of a solar power racking system. Determining the appropriate modularity of the system is shown to be necessary to this analysis. Finally, the need for modeling and simulation in this analysis is expressed.

3.1. What-If Analysis for Modular Design

For the most part, Modular design is beneficial to the product over its lifecycle. But modularity can be created in many different ways, each of which has implications for product performance. In most SPRS systems, modularity permits customization to a variety of applications. But it also increases the number of parts and steps required to assemble and install a system. The goal then is to reduce part count and installation time, while maintaining or increasing customizability. This requires analysis of the lifecycle, and the ability to measure impacts on it of various design modifications. By performing a what-if analysis for the different configurations or design variants, the decision maker can select an SPRS that can meet the requirements of the application at the lowest lifecycle cost.

3.1.1. SPRS Design

An SPRS like all products has primary requirements it must meet to be applicable to a solar power system. These requirements are:

- Must withstand wind and snow loads
- Must be applicable to a wide variety of supporting structures (like roofs)
- Must last 25 years
- Must be easy to install
- Must work with standard panels
- Must support wire management

An abstraction and functional decomposition of a typical SPRS can be used to understand how the system fulfills these requirements. This abstraction also permits the differentiation of parts that fulfill different functions and sub functions they fulfill. Part variants that fulfill the same function can be differentiated by the “flow of material, signals and energy” through them[42]. As discussed in the literature review on modularity, the abstraction, analysis and selection of part variants can affect the modularity of the SPRS.

In the manufacturing stage, changes to design modularity can be used to change the distribution of added value between material, utilization and labor. Incorporating more functions into fewer parts can help sway the distribution towards higher utilization costs, and lower material and labor costs. Moving in the opposite direction, by increasing the number of parts and decreasing the number of functions fulfilled per part, contributions of added value from materials and labor increase relative to utilization.

Decisions on degree of modularity at the manufacturing stage are therefore influenced by material, labor and utilization costs. High labor costs may cause decreased modularity so as to reduce the number of parts that need to be assembled. High material costs would also have the same effect. High utilization costs but low material and labor costs may serve to increase modularity through increased part count.

Since the installation stage is primarily a labor driven stage, it would most likely benefit from a lower level of modularity. This is because fewer parts/assemblies result in fewer installation steps. For example a SPRS with rails, feet and clamps that need to be assembled and installed on site will require activities that install or assemble each in order to complete the SPRS. However, strategies other strategies can be utilized to reduce the number of installation steps and still maintain the same level of modularity. Taking the SPRS example again, the rails, feet and clamps could be pre-assembled as part of the manufacturing process. When they arrived on site, it would then only take one set of activities for the assembly instead of sets of activities for each part. This of course has implications for the manufacturing stage, which will now see an increase in the labor added value. Decisions such as these will therefore be influenced by the difference in labor costs between onsite installation and factory assembly.

Maintenance cost reduction benefits from high modularity, since modularity makes it easy to identify and replace faulty components. At the extreme case where each part supports a different function, it usually doesn’t take much trouble to identify the fault since it is not obfuscated by a plethora of functions being performed by the part. With enough data, parts prone to faults can be identified earlier and replaced before they fail, thus reducing downtime. Since modularity strategies also include reuse of parts, or standard components, the learning curve to identify and replace these components will not need to be repeated for every application. This saves maintenance time and reduces mistakes. Therefore unlike the installation stage, high modularity supports reduction of labor cost in the maintenance stage. But, once again the high modularity that benefits this stage may have different implications for the installation and manufacturing stages.

3.1.2. Technical Challenges

In the spectrum of modularity, how do you decide what level of modularity is best? The interactions of the various strategies outlined above are complex and often are not apparent. Modularity strategies that benefit one stage often impact another stage adversely. Therefore design decisions must take this into account. The goal of the designer or decision maker then is to identify and implement strategies that have the lowest net adverse impact. For the purposes of this paper, this lowest net impact results in the lowest lifecycle cost of the SPRS. This is why a what if analysis for various changes is required. There are several obstacles to meeting this challenge. First, each design must be evaluated for level of modularity. Second, the designs should be reviewed to determine whether the level of modularity meets the design intent. Finally, the designs can be compared relative to cost to gauge the modularity sweet spot.

3.2.3. Technical Approach

The solution to this technical challenge lies appropriately measuring the modularity of the system. Once an appropriate method of measuring modularity has been determined, designs, their variants, or the competition can be evaluated to determine their modularity metric. In doing so these designs are assigned a characteristic measure that can be used to differentiate them. Modeling, data collection, and then simulation can help tie cost performance to modularity. As a result, it may be possible to identify trends in cost related to changes in modularity for closely related systems. For systems with significant differences, this measure is simply a way to show that these systems are indeed different, and that the cost difference may be a result of a difference in modularity, but with less certainty.

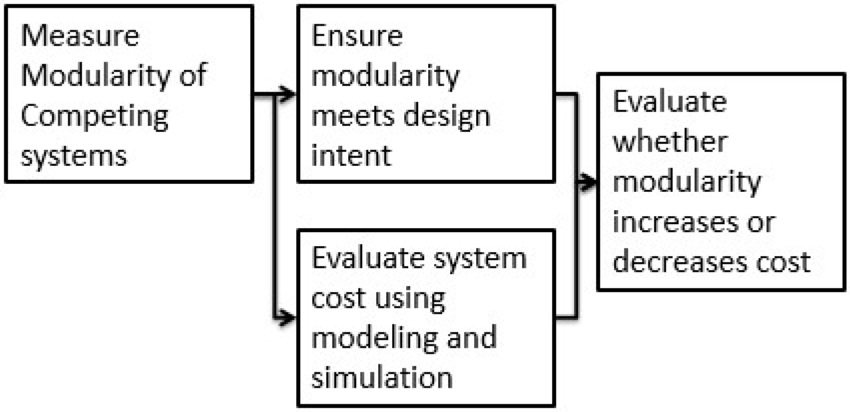


Figure 3.2.3.1 Modular Design Technical Approach

3.2. Solar Power Racking System Model

3.2.1. Solar Power Racking System

The Solar Power Racking System (SPRS) attaches the photovoltaic modules to a structurally stable surface. The cost it adds to a system can be divided into material, equipment utilization, and labor contributions. Material contributions are determined by the cost and quantity of materials utilized to construct the system. The process of shape forming and fabrication that converts materials into usable geometry utilizes a variety of equipment, the cost of which is amortized over its period of use to create the geometry. This contributes to the equipment utilization cost, or capital cost component. The labor used to produce, install and maintain the system, provides the labor cost component. Reductions in these costs through lifecycle analysis, modular design, modeling and simulation can result in a lowering the cost contributions of each of these components. This in turn will support lowering the levelized cost of the system.

3.2.2. SPRS Lifecycle

An SPRS has three main lifecycle stages, which are similar to that of the solar power system as a whole. Its life begins with the manufacturing stage where raw materials are converted into the components that form the physical system. The next major stage consists of installing the system on a site and based on a predefined installation plan. The third major stage is the maintenance stage, during which system components are cleaned and replaced as needed to support optimum functioning of the system. Each of these stages varies with respect to time domain of activities (hrs, minutes, etc.), and distribution of value addition between material, equipment utilization and labor. As a result, the cost performance of the system is sensitive to the interactions between the designs of the system and the attributes of each of these stages.

The manufacturing stage consists of a time domain measured in hours and minutes. Activities in this stage include cutting, drilling, gluing, extruding, painting, etc. The distribution of the value addition during these activities is dependent on material cost, level of automation, cost of labor, and efficiency of the process (which is usually a function of age of the process). These attributes often vary by manufacturer and location of the facility. For example, manufacturing facilities are often highly automated and are designed to minimize labor. This typically results in a dominance of equipment utilization costs in the overall production cost. In developing countries, where labor rates and technological proficiency are low, there is dominance of labor cost or material cost in the overall cost production. A lifecycle cost analysis of this stage will help identify the distribution of costs, and in so doing facilitate cost reduction efforts.

The installation stage is universally a labor cost driven stage and its time domain is measured in hours and days. The stage typically consists of material staging, assembly of sub systems, preparation of installation locations, and component installation. This is a labor driven stage because the high variability of applications prevents cost effective automation. Material cost is also a negligible contributor since most of the material costs have already been embedded in the system during production. There is some utilization of mobile equipment such as drills, cranes, ladders, etc., which must be taken into account. Most of the cost variation typically results from site differences and labor rates. For example, installation on a sloped roof involves many more installation steps that require manual activities than installation on a field. Sloped roofs come in a variety of slopes and can have a large variation in structural attributes. This makes it difficult to create a standardized system to attach to them. As a result several labor-intensive steps are required to attach the racking system. A field on the other hand is almost always flat and can have standard attachment configurations applied to it.

The maintenance stage is also a labor cost driven stage, but this stage's time domain is measured in months and years. Activities during this stage involve cleaning, replacing damaged components, and routine checks. For a stable system, labor cost is usually the largest cost contributor unless there is a need to replace major system components such as panels. This is the most difficult stage to analyze for cost since there is a large variability of maintenance tasks and frequency. These are often climate dependent, since extreme climates are more likely to cause damage to systems. For example, an area prone to hail storms will see a higher rate of panel replacement activities.

3.2.3. Lifecycle Cost

Materials, equipment utilization and labor are the major contributors to the lifecycle cost of the system. Values of these when collected can be included in lifecycle cost models similar to **Error! Reference source not found.**. These must be obtained over the three main phases of the lifecycle in order to obtain a relatively holistic lifecycle cost. The accuracy of this lifecycle cost value can be estimated based on the estimators and variance parameters of the material, utilization and labor cost components. The aggregate variance of the lifecycle cost determined as a result of this can be used to determine a confidence interval for the cost value. As a result, decision makers can then evaluate the sensitivity of this parameter and its variance to design changes, or compare different systems with different parameter values and variances. This helps avoid the pitfalls of overestimating and underestimating as illustrated by Figure .

3.3.1. System Modeling

The first step to understanding a system is being able to describe it. Modeling of systems has been recognized as an effective way to accomplish this. Currently, there is no standard way to model SPRS's in a form that describes its lifecycle performance. Different entities utilize different software packages and process specific to their area of expertise. The methods of description also differ with respect to stage of life, and in many cases the installation and maintenance stages are neglected. But a good system description is essential to designers and decision makers. It should include not only geometric attributes, but also meta data such as assembly sequences, process times, resources and equipment utilization. This detailed description will permit a more thorough review at each phase of the lifecycle and allow for better design and selection decisions.

At the manufacturing stage of an SPRS, current modeling methods comprise of cad drawings and process diagrams. CAD drawings are supplied by the design department and process diagrams are created by the manufacturing engineering group. Process diagrams are usually created after a design is complete, and are used to optimize the production of the new design based on existing equipment and layouts, or to procure new equipment and change layouts. The communication is heavily weighted in the direction flow from Designers to manufacturers, since most changes begin with changes to the CAD drawings. The interactions between designers and manufacturing are therefore primarily conducted through meetings and conference calls. During these interactions design changes are evaluated for impact on manufacturing processes, but the comprehensiveness and accuracy of these estimates is dependent on the experience of the parties involved. In fact this is one of the reasons why it takes a long time to train a design and manufacturing engineer. In some more advanced facilities and design environments, interactions may be informed by a formal process, such as an FMEA or DFM tool. But these are often not part of the process for many SPRS manufacturers who are relatively new and have not yet felt the competitive pressure to implement these processes.

The installation stage is typically influenced by installation and assembly documentation provided by the manufacturer. The manufacturer does involve installers at the design stage when the assembly and installation sequences are being thought through. However, designs are being updated and changed frequently and it is difficult to ensure that all aspects of the installation process are considered when gauging the impact of the design change. In fact, there is little or no means to comprehensively capture the design process from the perspective of the installer and this can often lead to designs that perform poorly during installation. For example in many rooftop systems, installers often spend an inordinate amount of time looking for rafter or structural members to which to connect the SPRS. These structural members are hidden under the roof surface and are typically found using sound differentials between different areas of the roof. This process is not captured effectively and is therefore often neglected in SPRS design.

The maintenance stage is typically described through the use of maintenance schedules, if there is any description at all. With the advent of solar power as a service, this is becoming more common as solar installations begin to be seen as capital assets that need routine maintenance in order to ensure the highest ROI. However, these schedules are often not taken into consideration at the design stage and are developed once again by the installers and companies managing the systems. There is no standard ontology linking maintenance with design, manufacturing or installation. The industry is also very new which is another reason why this has not yet been developed to the extent it has in the automotive sector, for example.

3.2.4. Technical Challenges

The main challenge is that of accurately describing the system. The description of the system is required to create an appropriate model that can be understood by multiple entities. This is often difficult for SPRS installation and maintenance stages since they are highly variable. For example a job with few panels to install may require only one truck load of equipment which can be onsite for the duration of the job. A larger job requiring many more panels may need multiple trucks which would be too expensive to have remain on site. Therefore the staging for this scenario may need additional steps to unload all the trucks that cannot remain on site, and organize them in a way that material can still be accessed as needed. Understanding and effectively capturing the most representative scenario is key to meeting this challenge.

3.2.5. Technical Approach

The approach to meet the main technical challenge will be to first develop a methodology that will help move from field data to a model that can be understood by multiple stakeholders. This methodology will be based on LCA methodologies described in the literature review, and include modifications to suit the goal of accurate model creation. The four stages of a typical LCA analysis have been used extensively in industry to describe systems in a lifecycle context and therefore is a robust basis. The result of applying the adapted LCA method will be a representative model described using industry standard modeling format. This industry standard format will help communicate the system description to multiple stakeholders.

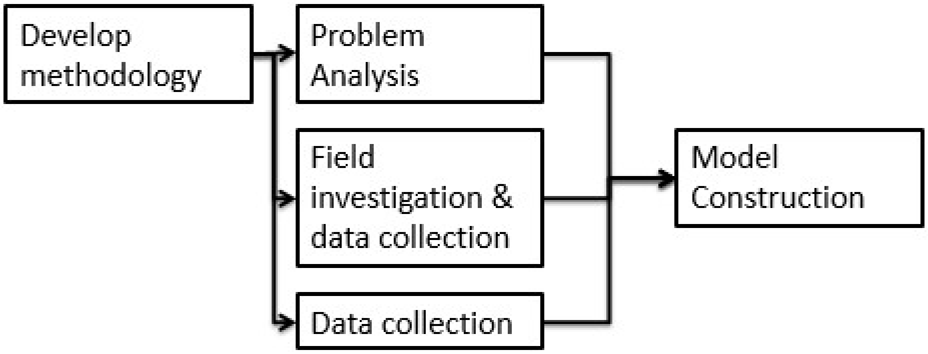


Figure 3.2.5.1 System Modeling Technical Approach

3.3 System Modeling and Simulation analysis

SPRS's come in a variety of configurations. The solar power industry is awash in systems that purport to provide some improvement that is of importance to the customer. These varieties also derive from different commercial domains. Installers have developed some SPRS's based on their experience in the field. Other SPRS's are developed by module manufacturers in a bid to make their module the preferred choice. Some of the domain variations arise from the use of different methods to design and improve designs. These methods have their own ontologies and significant issues arise when these ontologies need to interact. Issues such as when installers want to improve module design but cannot understand the module manufacturer's schematics because they are used to installation oriented ontology. These differences in ontology have significant consequences for comparison of systems since they reduce the likelihood of a common basis of comparison. Therefore without some standard ontology to describe systems, it is difficult to effectively identify a superior design or to identify what attributes make it superior.

3.3.2. System Simulation

It is not enough to obtain an estimate of a parameter such as production time or labor cost. An understanding of the variance is a necessary part of the efficacy of this estimate. For example, product A has a total labor cost of $10 and a variance of 1, product B has a cost of 9 dollars and a variance of 5, and there is a penalty of $5 every time the cost exceeds $11. In this situation, even though product B is cheaper, its larger variance implies that its actual cost will be higher. The higher variance may capture effects such as a high variability in lead-time, or frequent stock outs. The penalty may be due to loss of business due to missing delivery targets or the bullwhip effect, for example. This simple example helps illustrate the importance of variance in the consideration of estimated parameters. Therefore it is important to obtain variance information for the manufacturing, installation and maintenance of SPRS's, in addition to modeling. One way to accomplish this is through the use of discrete event simulation.

Discrete event simulation of manufacturing processes is common. Since it is already being used to estimate such parameters as resource utilization, overall processing time, and labor cost, it can be inferred that it is fulfilling the need for these. The extent of its use in SPRS production is currently unknown, but it is likely to be very low. However, SPRS's stand to benefit from this just as automobile manufacturing, electronics manufacturing and even solar module manufacturing have benefited from discrete event simulation. Apart from providing variance estimates for parameters, discrete event simulation also helps identify which processes or activities are contributing to the variance and parameter values. Such information is invaluable in process improvement, and can help further reduce the cost and cost variance over time.

Application of discrete event simulation to SPRS installation and maintenance is non-existent. Therefore it could provide an effective tool to quantify the variability in installation and maintenance activities. Such quantification can help with an analysis and implementation of lean installation and maintenance. In doing so, significant cost savings could be obtained through optimizations of labor type allocation, task sequencing, and job planning. For example, if roofers instead of installers can perform activities such as attachment of rail connections to the roof, significant labor savings can be realized since roofers cost less per hour than installers. Job planning benefits when the durations of installation or maintenance activities can be accurately estimated. This could allow more jobs to be completed per day, which will lower the cost of overhead per watt installed.

3.3.3. Technical Challenges

The primary challenges in simulating a system over its lifecycle is to obtain representative performance data, and then convert it into a form that can be used in the simulation. Obtaining the right data in solar power systems is difficult because of the large variations in system types and activities. Further, when developing a conceptual system, no data may yet exist. On the rare occasion that data does exist, it must be converted into a form that can be used by the simulation method. For stochastic simulation, this if often the form of a distribution.

3.3.4. Technical Approach

Tackling the first challenge requires a combination of efforts. In some instances data may already be available and can be used directly. In others, the designer will need to estimate the parameters for each activity. In the case of comparing two systems then, the designer will need to remain consistent with the estimations. In these situations where no data is available, the design can directly input the parameters into the simulation model. For this framework, we will be using discrete event simulation and most platforms such as arena allow parameters to be directly input into the model.

For the cases where data is available the second technical challenge will need to be addressed. In these cases some pre-processing is required. This pre-processing usually involves generating a distribution using the data. Often, multiple distributions can be fit to the data, and so there is a need to evaluate ones that fit the best. Goodness of fit can be evaluated using the Chi-Square goodness of fit test and/or the Kolmogorov-Smirnov test among others. Once a distribution is selected, the parameters can be input into the simulation model.

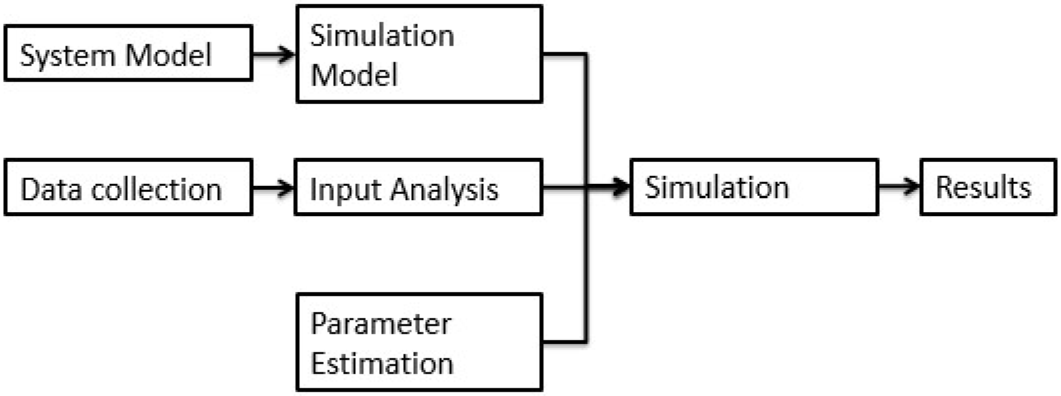


Figure 3.3.4.1 Simulation Analysis Technical Approach

3.4. Summary

In this section three main aspects of SPRS labor cost analysis were discussed. Lifecycle analysis, what if analysis for modular design, and simulation for comparison of SPRS, were presented with respect to the different stages of the SPRS lifecycle. Technical challenges relating to each of these aspects were also identified and discussed in detail. Finally, strategies for meeting these challenges were proposed and will be evaluated in detail in the subsequent sections.

CHAPTER 4

MODULAR DESIGN OF SOLAR POWER SYSTEMS

Modularity of any system can be Functional or Structural [43]. Ji et al. [43] include Material as another component of modularity. In this paper the method proposed by Ji et al.[43] will be used to measure the modularity of systems under consideration. The method begins by evaluating the functional and structural similarity, leading to a holistic modularity metric. Material reuse similarity can be added for a more comprehensive modularity measure, but will not be considered in this paper for the sake of brevity.

4.1. Measuring Modularity

4.1.1 Functional Similarity

Functional similarity has been explored by various notable papers. Taking into consideration the flow of energy, signals and materials, Pahl and Beitz [44] propose a functional decomposition diagram to determine functional similarity. This type of analysis can be coupled with a morphological matrix to create multiple design variants that satisfy the same needs but in different ways. In fact the differences between functions can be characterized by the differences in these flows [42]. Yu et al. [45] highlight that when two components contribute to the realization of specific functions, this relationship affects the strength between them. Several of these views of functional similarity are synthesized by Ji et al.[43] into an evaluation of functional similarity via "three similarity attributes, namely functional connection pattern, functional compatibility, and functional configuration pattern," which they express as v_{ij}^{h1} , v_{ij}^{h2} and v_{ij}^{h3} . The values for these can be specified according to the following tables taken from their paper:

Table 4.1.1.1 Grade criteria for the functional connection pattern [43]

Grade Criteria	Value
Same level subordinate function of main function	0.9
Different level subordinate function of main function	0.3
Different subordinate functions of different main functions, but have the input/output function relationship	0.1
Others	0

Table 4.1.2.2 Grade criteria for the functional compatibility [43]

Grade Criteria	Value
Can exist in a product concurrently, and function fulfillment of a component is necessary to the other	0.9
Can exist in a product concurrently, and function fulfillment of a component is accessorial to the other	0.3
Can exist in a product concurrently, but they are irrelevant	0.1
Cannot exist in a product concurrently	0

Table 4.1.3.3 Grade criteria for the functional configuration pattern [43]

Grade Criteria	Value
Both are the necessary and basic function to product	0.9
One is necessary, and the other is optional to product	0.3
Both are the unnecessary and Optional function to product	0.1

4.1.2 Structural Similarity

The physical state of components enables the realization of functions [46] [43]. A physical structure can be "described as geometric positions and connection forms of components, such that a geometric position can be measured by the degree of freedom of the components, whilst a connection form is measured by the welds, fasteners, spacing, etc." [43] [47]. Ji et al.[43] in a manner similar to functional similarity synthesized these into attributes such as "component connection pattern, component assembly tolerance, and component position pattern" [43]. "These structural similarity attributes can be expressed as v_{ij}^{s1} , v_{ij}^{s2} and v_{ij}^{s3}, respectively" [43], and their values can be specified according to the following tables:

Table 4.1.2.1 Grade criteria of the component connection pattern [43]

Grade Criteria	Value
Constrained by several contact faces	1
Constrained by several contact points	0.8
Constrained by one contact face	0.6
Constrained by one contact line	0.4
Constrained by one contact point	0.2
No connection	0

Table 4.1.2.2 Grade criteria of the component assembly tolerance [43]

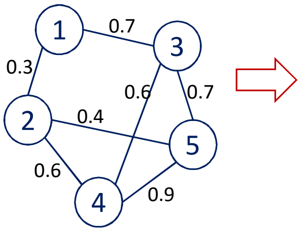
Grade Criteria	Value
All contact faces need higher tolerance	1
Part of contact faces need higher tolerance	0.6
No special tolerance request for all contact faces	0.3
No connection	0

Table 4.1.2.3 Grade criteria of the component position pattern [43]

Grade Criteria	Value
0 degree of freedom	1
1 degree of freedom	0.8
2 degree of freedom	0.6
3 degree of freedom	0.4
4 degree of freedom	0.2
5 degree of freedom	0.1
No connection	0

4.1.3 CCF-Based component similarity measure

"Components possessing a higher component connection force (CCF) will have a higher possibility to be clustered into one module" [45] [43]. CCF liaison networks expressed as a correlation matrix, can be developed to show "pairwise relationships between components"[43]. "The CCF can be applied to a group of components by aggregation" [43], and "the prevailing approach to CCF aggregation is by weighted sum"[48] [43]. By applying this to the correlation matrices for each of the functional and structural measures, the stage can be set to determine a holistic modularity measure.



	c_1	c_2	c_3	c_4	c_5
c_1	0	0.3	0.7	0	0
c_2	0.3	0	0	0.6	0.4
c_3	0.7	0	0	0.6	0.7
c_4	0	0.6	0.6	0	0.9
c_5	0	0.4	0.7	0.9	0

Fig. 4.1.3.1 CCF-based liaison network and the corresponding correlation matrix[43]

4.1.4. Holistic Modularity Measure

Guo [49] presents a total modularity metric “by subtracting the average CCF within modules from the average CCF between modules” [43]. In doing so tightly coupled modules are rewarded and connections in between modules are penalized[43]. The final metric ranges from -1 to 1, where negative values indicate more connections between modules than within[43]. Ji et al[43] formulate the metric as:

$$M_{G\&G} = \frac{\sum_{k=1}^{N_m}\left(\sum_{i=n_k}^{m_k}\sum_{j=n_k}^{m_k} R_{ij}/(m_k-n_k+1)^2\right) - \sum_{k=1}^{N_m}\left(\sum_{i=n_k}^{m_k}\left(\sum_{j=1}^{n_{k-1}} R_{ij} + \sum_{j=m_{k+1}}^{N_c} R_{ij}\right)/(m_k-n_k+1)(N_c-m_k+n_k-1)\right)}{N_m}$$

4.1.4.1[43]

where

n_k is the index of the first component in the *k*-th module;

m_k is the index of the last component in the *k*-th module;

N_m is the total number of modules in the product;

N_c is the total number of components in the product; and

R_{ij} is the CCF of components C_i and C_j in the product.

4.2. MegaModule case study

The commercial system and MegaModule system have different levels of modularity. The difference in modularity can be quantified using the modularity measure developed by Guo et al. [49]. Before this can be done however, a correlation matrix must be developed using the methodology proposed by Ji et al. [43]. The first step in their method is to create a component list for each product. Then, correlation matrices are created for different dimensions of modularity. These are aggregated into a final correlation matrix which is used to calculate the modularity metric.

4.2.1. Creation of a Component List

The commercial system and MegaModule system parts lists were used to create a component lists for each, as shown in Tables 4.1.1.1. and 4.1.1.2. below. The components lists include a unique component number for each part, and includes a description of the component function and material.

Table 4.2.1.1 Commercial System component list

Commercial system			
#	Name	Main Function	Material
C1	Laminate	Convert sunlight into electricity	Composite
C2	Frame	Strucural support of laminate	Aluminum
C3	Jbox	Transfer electricity from	Polymeric
C4	Grounding Lug	Bond grounding cable to Frame	Aluminum
C5	Grounding cable	Bond System	Copper
C6	Panel clamp	Attach module to rail	Aluminum
C7	Clamp fastener	Attach clamp to rail	Stainless steel
C8	Rail	Structural support for system	Aluminum
C9	Feet	Attach rails to roof	Aluminum
C10	Feet fastener	Attach feet to roof	Stainless steel
C11	Bypass Diodes	Reduce hot spots	Composite

Table 4.2.1.2. MegaModule component list

MegaModule system			
#	Name	Main Function	Material
C1	Laminate	Convert sunlight into electricity	Composite
C2	Polymeric Restraints	Attach laminates to frame, house electricals and transfer electricity	PVC/ABS/HDPE
C3	Frame	Strucural support of laminate	Aluminum
C4	Boomerang	Attach module to Solar Ridge	Steel
C5	Bypass Diodes	Reduce hot spots	Composite

4.2.2. Creation of Correlation Matrices

Correlation matrices were created for the commercial system and the MegaModule system, using the criteria provided by Ji et al.[43]. Matrices were created for functional and structural similarity, and material reuse similarity was left out since the team was not concerned with material reuse at this time. The similarity matrices for each dimension are shown below.

Table 4.2.2.1 Commercial System – Functional Connection Pattern

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
C2	0.3	0	0	0.1	0.1	0.9	0.9	0.9	0.9	0.9	0
C3	0.1	0	0	0	0	0	0	0	0	0	0
C4	0.1	0.1	0	0	0.9	0.9	0	0	0	0	0
C5	0.1	0.1	0	0.9	0	0.1	0	0	0	0	0
C6	0.1	0.9	0	0.9	0.1	0	0.9	0.9	0.3	0.3	0
C7	0.1	0.9	0	0	0	0.9	0	0.9	0.3	0.3	0
C8	0.1	0.9	0	0	0	0.9	0.9	0	0.9	0.9	0
C9	0.1	0.9	0	0	0	0.3	0.3	0.9	0	0.9	0
C10	0.1	0.9	0	0	0	0.3	0.3	0.9	0.9	0	0
C11	0.1	0	0	0	0	0	0	0	0	0	0

Table 4.3.2.2 MegaModule – Functional Connection Pattern

	C1	C2	C3	C4	C5
C1	0	0.1	0	0	0.3
C2	0.1	0	0.9	0.3	0
C3	0	0.9	0	0.9	0
C4	0	0.3	0.9	0	0
C5	0.3	0	0	0	0

Table 4.2.2.3 Commercial System – Functional Compatibility

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0	0.9	0.9	0.3	0.9	0.3	0.3	0.9	0.9	0.9	0.9
C2	0.9	0	0.1	0.3	0.9	0.9	0.9	0.9	0.9	0.9	0.1
C3	0.9	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
C4	0.3	0.3	0.1	0	0.9	0.1	0.1	0.1	0.1	0.1	0.1
C5	0.9	0.9	0.1	0.9	0	0.1	0.1	0.1	0.1	0.1	0.1
C6	0.3	0.9	0.1	0.1	0.1	0	0.9	0.9	0.1	0.1	0.1
C7	0.3	0.9	0.1	0.1	0.1	0.9	0	0.3	0.1	0.1	0.1
C8	0.9	0.9	0.1	0.1	0.1	0.9	0.3	0	0.9	0.9	0.1
C9	0.9	0.9	0.1	0.1	0.1	0.1	0.1	0.9	0	0.9	0.1
C10	0.9	0.9	0.1	0.1	0.1	0.1	0.1	0.9	0.9	0	0.1
C11	0.9	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0

Table 4.2.2.4 MegaModule – Functional Compatibility

	C1	C2	C3	C4	C5
C1	0	0.9	0.9	0.1	0.9
C2	0.9	0	0.9	0.1	0.9
C3	0.9	0.9	0	0.9	0.1
C4	0.1	0.1	0.9	0	0.1
C5	0.9	0.9	0.1	0.1	0

Table 4.2.2.5 Commercial System - Functional Configuration pattern

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
C2	0.9	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
C3	0.9	0.9	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
C4	0.9	0.9	0.9	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9
C5	0.9	0.9	0.9	0.9	0	0.9	0.9	0.9	0.9	0.9	0.9
C6	0.9	0.9	0.9	0.9	0.9	0	0.9	0.9	0.9	0.9	0.9
C7	0.9	0.9	0.9	0.9	0.9	0.9	0	0.9	0.9	0.9	0.9
C8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0	0.9	0.9	0.9
C9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0	0.9	0.9
C10	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0	0.9
C11	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0

Table 4.2.2.6 MegaModule - Functional Configuration pattern

	C1	C2	C3	C4	C5
C1	0	0.9	0.9	0.3	0.9
C2	0.9	0	0.9	0.1	0.9
C3	0.9	0.9	0	0.9	0.1
C4	0.3	0.1	0.9	0	0.1
C5	0.9	0.9	0.1	0.1	0

Table 4.2.2.6 Commercial System, Structural Similarity – Component Connection Pattern

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0	1	0.6	0	0	0	0	0	0	0	0
C2	1	0	0	0.6	0	1	0	0.6	0	0	0
C3	0.6	0	0	0	0	0	0	0	0	0	0.8
C4	0	0.6	0	0	0.8	0	0	0	0	0	0
C5	0	0	0	0.8	0	0	0	0	0	0	0
C6	0	1	0	0	0	0	0.6	0.8	0	0	0
C7	0	0	0	0	0	0.6	0	0.8	0	0	0
C8	0	0.6	0	0	0	0.8	0.8	0	1	0	0
C9	0	0	0	0	0	0	0	1	0	0.6	0
C10	0	0	0	0	0	0	0	0	0.6	0	0
C11	0	0	0.8	0	0	0	0	0	0	0	0

Table 4.2.2.7 MegaModule, Structural Similarity – Component Connection Pattern

	C1	C2	C3	C4	C5
C1	0	1	0	0	0.8
C2	1	0	1	0	1
C3	0	1	0	1	0
C4	0	0	1	0	0
C5	0.8	1	0	0	0

Table 4.2.2.8 Commercial System, Structural Similarity – Component Assembly Tolerance

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0	1	0.3	0	0	0	0	0	0	0	0
C2	1	0	0	0.3	0	0	0	0	0	0	0
C3	0.3	0	0	0	0	0	0	0	0	0	0.3
C4	0	0.3	0	0	0.3	0	0	0	0	0	0
C5	0	0	0	0.3	0	0	0	0	0	0	0
C6	0	0	0	0	0	0	0.3	0.3	0	0	0
C7	0	0	0	0	0	0.3	0	0.3	0	0	0
C8	0	0	0	0	0	0.3	0.3	0	0.3	0	0
C9	0	0	0	0	0	0	0	0.3	0	0.3	0
C10	0	0	0	0	0	0	0	0	0.3	0	0
C11	0	0	0.3	0	0	0	0	0	0	0	0

Table 4.2.2.8 MegaModule, Structural Similarity – Component Connection Pattern

	C1	C2	C3	C4	C5
C1	0	0.9	0	0	0
C2	0.9	0	0.3	0	0.3
C3	0	0.3	0	0.3	0
C4	0	0	0.3	0	0
C5	0	0.3	0	0	0

Table 4.2.2.9 Commercial System, Structural Similarity – Component Position Pattern

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	
C1	0	1	1	0	0	0	0	0	0	0	0
C2	1	0	0	1	0	0	0	0	0	0	0
C3	1	0	0	0	0	0	0	0	0	0	0.8
C4	0	1	0	0	1	0	0	0	0	0	0
C5	0	0	0	1	0	0	0	0	0	0	0
C6	0	0	0	0	0	0	1	1	0	0	0
C7	0	0	0	0	0	1	0	1	0	0	0
C8	0	0	0	0	0	1	1	0	1	0	0
C9	0	0	0	0	0	0	0	1	0	1	0
C10	0	0	0	0	0	0	0	0	1	0	0
C11	0	0	0.8	0	0	0	0	0	0	0	0

Table 4.2.2.10 MegaModule, Structural Similarity – Component Position Pattern

	C1	C2	C3	C4	C5
C1	0	1	0	0	1
C2	1	0	1	0	1
C3	0	1	0	1	0
C4	0	0	1	0	0
C5	1	1	0	0	0

4.2.3. Aggregation of Correlation Matrices

Since this is a very early stage modularity analysis, the team decided to apply equal weight to each modularity dimension. The tables below show aggregated values for each dimension and then the final CCF matrix. The final aggregation is the average of the CCF through all dimensions of similarity.

Table 4.2.3.1 Commercial System, Functional Similarity CCF

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0.00	0.70	0.63	0.43	0.63	0.43	0.43	0.63	0.63	0.63	0.63
C2	0.70	0.00	0.33	0.43	0.63	0.90	0.90	0.90	0.90	0.90	0.33
C3	0.63	0.33	0.00	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
C4	0.43	0.43	0.33	0.00	0.90	0.63	0.33	0.33	0.33	0.33	0.33
C5	0.63	0.63	0.33	0.90	0.00	0.37	0.33	0.33	0.33	0.33	0.33
C6	0.43	0.90	0.33	0.63	0.37	0.00	0.90	0.90	0.43	0.43	0.33
C7	0.43	0.90	0.33	0.33	0.33	0.90	0.00	0.70	0.43	0.43	0.33
C8	0.63	0.90	0.33	0.33	0.33	0.90	0.70	0.00	0.90	0.90	0.33
C9	0.63	0.90	0.33	0.33	0.33	0.43	0.43	0.90	0.00	0.90	0.33
C10	0.63	0.90	0.33	0.33	0.33	0.43	0.43	0.90	0.90	0.00	0.33
C11	0.63	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.00

Table 4.2.3.2 MegaModule, Functional Similarity CCF

	C1	C2	C3	C4	C5
C1	0.00	0.63	0.60	0.13	0.70
C2	0.63	0.00	0.90	0.17	0.60
C3	0.60	0.90	0.00	0.90	0.07
C4	0.13	0.17	0.90	0.00	0.07
C5	0.70	0.60	0.07	0.07	0.00

Table 4.2.3.3 Commercial System, Structural Similarity CCF

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0.00	1.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63
C2	1.00	0.00	0.00	0.63	0.00	0.33	0.00	0.20	0.00	0.00	0.33
C3	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33
C4	0.00	0.63	0.00	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.33
C5	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.33
C6	0.00	0.33	0.00	0.00	0.00	0.00	0.63	0.70	0.00	0.00	0.33
C7	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.70	0.00	0.00	0.33
C8	0.00	0.20	0.00	0.00	0.00	0.70	0.70	0.00	0.77	0.00	0.33
C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.00	0.63	0.33
C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.33
C11	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 4.2.3.4 MegaModule, Structural Similarity CCF

	C1	C2	C3	C4	C5
C1	0.00	0.97	0.00	0.00	0.60
C2	0.97	0.00	0.77	0.00	0.77
C3	0.00	0.77	0.00	0.77	0.00
C4	0.00	0.00	0.77	0.00	0.00
C5	0.60	0.77	0.00	0.00	0.00

Table 4.2.3.5 Commercial System - Aggregated CCF

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0.00	0.85	0.63	0.22	0.32	0.22	0.22	0.32	0.32	0.32	0.32
C2	0.85	0.00	0.17	0.53	0.32	0.62	0.45	0.55	0.45	0.45	0.17
C3	0.63	0.17	0.00	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
C4	0.22	0.53	0.17	0.00	0.80	0.32	0.17	0.17	0.17	0.17	0.17
C5	0.32	0.32	0.17	0.80	0.00	0.18	0.17	0.17	0.17	0.17	0.17
C6	0.22	0.62	0.17	0.32	0.18	0.00	0.77	0.80	0.22	0.22	0.17
C7	0.22	0.45	0.17	0.17	0.17	0.77	0.00	0.70	0.22	0.22	0.17
C8	0.32	0.55	0.17	0.17	0.17	0.80	0.70	0.00	0.83	0.45	0.17
C9	0.32	0.45	0.17	0.17	0.17	0.22	0.22	0.83	0.00	0.77	0.17
C10	0.32	0.45	0.17	0.17	0.17	0.22	0.22	0.45	0.77	0.00	0.17
C11	0.32	0.17	0.48	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.00

Table 4.2.3.6 MegaModule - Aggregated CCF

	C1	C2	C3	C4	C5
C1	0.00	0.80	0.30	0.07	0.65
C2	0.80	0.00	0.83	0.08	0.68
C3	0.30	0.83	0.00	0.83	0.03
C4	0.07	0.08	0.83	0.00	0.03
C5	0.65	0.68	0.03	0.03	0.00

4.2.4. Comparison of modularity

Equation 4.1.4.1. is used to generate the modularity metric for each system. The aggregate CCF of component C_i and C_j is used as R_{ij}. The result is shown in Table 4.2.4.1. below.

Table 4.2.4.1. Modularity Metrics

MegaModue	0.68
Commercial System	0.09

The Mega module is calculated to have a higher modularity than the commercial system. This was the design intent and was therefore expected. This metric is a quantitative measure of the design intent, and proves that the two designs are sufficiently differentiated. This is important because it ensures that the results of the simulation being performed are relevant because of the difference in design.

4.3 Verification and Validation

The need to determine modularity is twofold. First, cost reduction is not proportional to an increase or decrease in modularity; i.e. there is a sweet spot at which cost is optimized. This requires a measure of modularity for which a cost can be determined, and then subsequent measures with related costs, so that the sweet spot can be discovered. Second, the modularity measure provides a method of differentiating between two different systems. For complex systems, this can support decision making in addition to visually represented information, drawings, specifications, costs, etc.

Chapter 4 presented the method proposed by Ji et al.[43] for a holistic modularity measure. It then applied this method to generate a modularity measure for the MegaModule and a typical roof mounted solar power racking system. The MegaModule was shown to have a higher modularity of 0.68 compared to a typical commercial system modularity of 0.09.

4.3. Summary

This chapter looked at the problem of defining modularity. The method proposed by Ji et al [40] was presented. This method utilizes functional and structural similarity to calculate a holistic modularity measure. The method was applied to the MegaModule case study to develop a modularity comparison between it and a typical commercial system.

CHAPTER 5

SYSTEM MODELING USING SYSML

In this section, a framework methodology for describing the SPRS will be presented. This framework will address many of the technical issues identified in the previous section and will support the development of a lifecycle cost analysis. The methodology described will use SysML as its primary ontology to support communication between many diverse groups involved in the process. It begins at a point where no consistent description of the system exists and ends with a SYSML diagram and data set to support discrete event simulation. The methodology will be described within the context of a case study, which will also serve as validation for the framework.

5.1. Methodology

The methodology used to generate a SYSML description follows four steps. First the problem must be analyzed to determine the necessary activities involved in obtaining the lifecycle cost. The second step is to perform a field investigation to identify the major activities taking place. This can be used to create an as is model for the system using a simple schematic notation. Next, detailed data on activity duration must be collected. Finally, a SYSML model can be created using the as-is model as a basis. It is important to create the SYSML model after data collection since the process of data collection may reveal variations in the process not apparent during the initial investigation. These variations can be accounted for by modifying the SYSML model appropriately and relative to the initial paper model.

Figure 5.1.1 Steps to create As-Is Model

5.1.1. Links to LCA Methodology

These four steps that lead to the development of an as-is model are analogous to those used to perform an LCA analysis. The activities that serve the problem analysis stage also serve the LCA goal and scope definition stage, and the end result is an understanding of the nature of the problem and the problem boundaries. The inventory analysis of LCA seeks to identify the various elements of the system and energy, mass and signal flows between them. The field investigation serves a similar purpose in that it seeks to identify the system and component interactions in reality. The Impact assessment stage of the LCA seeks to identify the effect of the various flows and components on the environment and human health. The data collection phase seeks to identify the impact of the process on the various parameters of interest. For example, in a study on labor utilization, the data collection will help identify the rates of labor use during each activity. Finally, an LCA synthesizes the information from all the phases through interpretation. The analog to this in the SPRS analysis is the creation of an As-Is model that represents the system in its entirety. The generation of a SysML model can be seen as an extension of the interpretation process since it captures the system relationships in more detail and in a standardized format.

5.2. Problem Analysis

The purpose of Step 1 is to analyze the problem and begin the process of obtaining a lifecycle cost. To do this the SPRS system must be analyzed at each stage of its lifecycle. The analysis for an SPRS that exists will differ from one that is still in the conceptual or embodiment design stage. An existing design will require a review of its bill of materials, manufacturing processes, installation activities and maintenance activities. A conceptual design may require conceptual development of manufacturing processes, installation activities and maintenance activities. Both systems will have areas of uncertainty because of missing or unknown data. These can be estimated using the expertise of the design team or individuals involved in manufacturing, installation, and maintenance. In the following subsections, the case study problem will be analyzed in detail.

5.3. Field Investigation and Data Collection

Field investigation and data collection typically involves on site observation of activities. For existing commercial systems, this can be accomplished by observers physically present during manufacturing, installation, and maintenance. For a system still on the drawing board, an existing system can be used as an analogous model [16] as long as the designer takes into account the differences between the two systems. While the activities are taking place, the observers must first generate a rough schematic of the process. The procedure detailed by Goodman et al [50]can then be used. According to this procedure, the collection team can utilize “flexible site logs to allow multiple observers to report time and motion data in a consistent manner across sites”. Raw data from the site can then be transferred to a data repository which is structured to[50]:

- “Enable time efficient and complete data entry” [50];
- “Support investigation of the data and testing of hypotheses” [50];
- “Enable data outliers identified in the analysis to be easily retrieved and investigated by preserving association with contextual parameters and field notes” [50].

5.4. As-Is Model construction

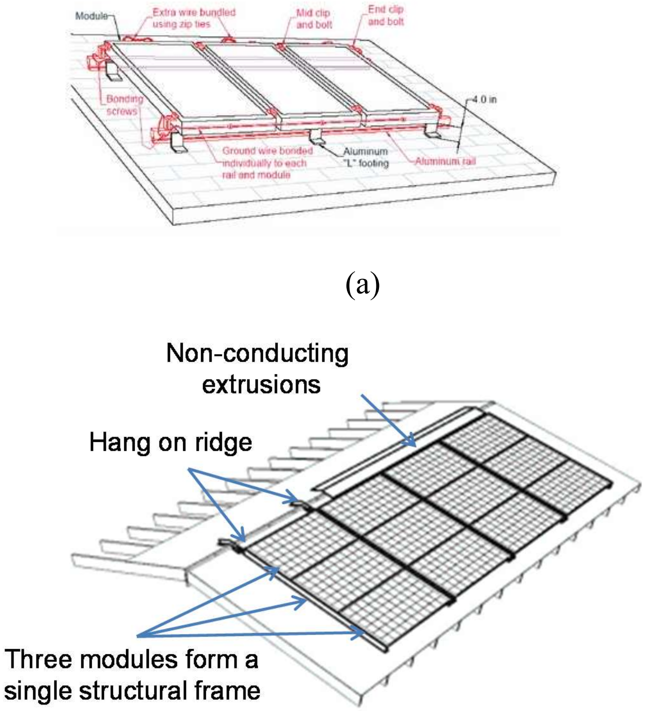
The As-Is model is a representation of the synthesis of information gathered in the prior stages. IDEF can be used to generate a very basic representation that can be easily understood by multiple stakeholders. For stakeholders who need more intelligence built into the model, the IDEF model can be used as a basis for a more intelligent SYSML model. The level of sophistication presented in each of these models can be tailored to meet the needs of the stakeholder’s that will use the information. Further, the paper model should be used to rapidly generate process representations during data gathering, and to quickly capture the variations in the process as separate representations. SYSML or a more intelligent modeling method should only be used once much of the variation in process has been understood, and can be represented efficiently with a small number of models.

5.5 MegaModule Case Study

5.2.1. MegaModule and Commercial SPRS Problem Analysis

This study seeks to identify the labor cost-effectiveness of a new solar power system known as a MegaModule. The MegaModule seeks to reduce the $/watt cost of residential SPRS’s, and team desires a quantification of its labor cost reduction. To accomplish this a typical commercial SPRS is used as a benchmark for comparison. By comparing the MegaModule with a typical commercial SPRS, the design team will be able to evaluate the extent and location of cost savings within the lifecycle. In doing so, the team can then determine whether the MegaModule meets its cost reduction goals, and if not, the level of modularity at which it could meet its goals.

A typical commercial SPRS consists of rails, feet, and module attachment components. The rails are structural components, designed to support the system and resist wind, snow and uplift loads. In order to resist these loads, the rails must be attached to structural roof members such as rafters. This is accomplished through the use of feet that attach to rafters via screws that penetrate the roof surface. This helps transfer forces from the rails directly to the rafters. Modules transfer down forces such as snow and wind loads directly to the rails. However, uplift wind loads are transferred to the rails via the attachment components that typical take the form of compression clips that are fastened to the rail and apply downward pressure to the module frame.



(a)

(b)

Figure 5.2.1.1 Illustration of (a) a typical commercial system[51] and (b) Mega Module on a roof ridge

5.2.2. MegaModule Data Collection

For the purposes of this case study, distributions of processing times for the manufacturing activities were assumed based on experience due to the fact that most of these activities are well understood in modern factories. For the commercial system, data for the installation phase was collected through actual onsite observations and interviews. However, the data for scheduled maintenance was obtained by decomposing it into sequential tasks whereas those for repair maintenance were collected based on the previous statistical analysis. For the Mega Module system, data were obtained based on the construction of the prototype and projections of performance over the long term and using the commercial system as an analog model.

Scheduled maintenance mainly include tasks of inspection, cleaning collector, checking collector glazing and seals, checking piping, duct and wiring insulation, checking roof penetration and support structures. These tasks are procedural and each task has a relatively stable distribution in terms of labor time. However, for the repair maintenance, it is more random. Based on an audit in June 2011 by New South Wales Fair Trading[52] in Australia, 658 solar panel systems were inspected, among which 122 (18.5%) were found to have major defects, such as unsafe wiring - either from a poor installation, broken panels, solar inverter fault - not working or showing warning lights, 418 (63.5%) were found to have minor defects, including general poor performance, and 118 (18%) were found to have no defects.

Based on this information, defects were categorized into three different kinds, i.e., major defects, minor defects, and no defects. We assume equal probabilities for each major defect (i.e., unsafe wiring, broken panels, and solar invert fault). The repair time is determined by the installation processes, such as rewiring, replacing broken panels, and replacing faulty solar inverters.

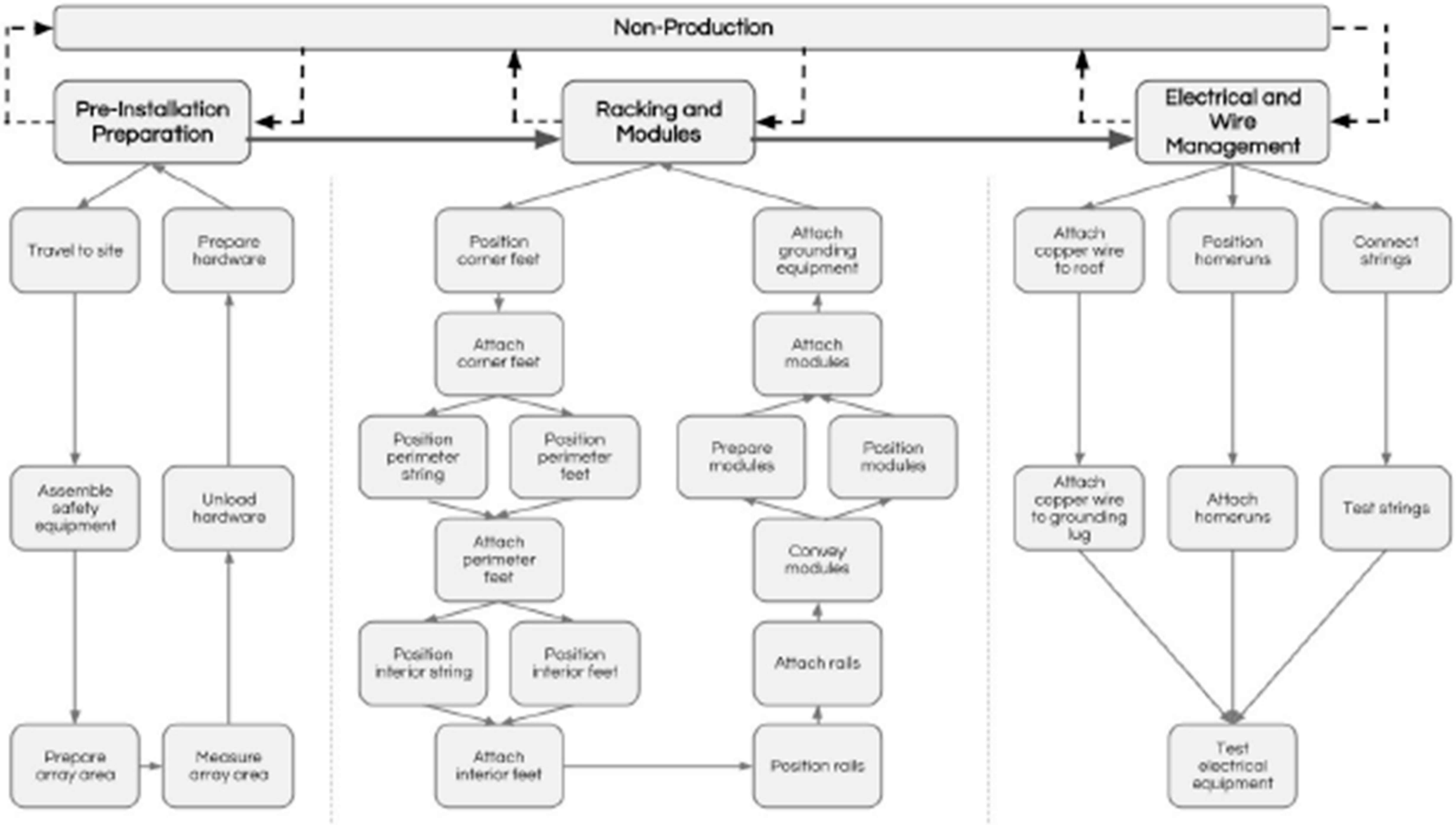


Figure 5.3.1.1 Activity sets for the installation process [50]

5.2.3. As-is Model

However, before building the SysML model of all the processes, overall structural models should be constructed for both the commercial system and the Mega Module system, respectively. The system structure is represented by block definition diagrams and internal block diagrams. The block definition diagrams describe the system hierarchy and system/component classifications, which are shown in Figure 5 and Figure 6 for the two solar power systems, respectively.

Based on the structure diagrams, the manufacturing, installation, and maintenance processes were modeled for both of the solar power systems. Their activity diagrams are shown from Figure 7 to Figure 12.

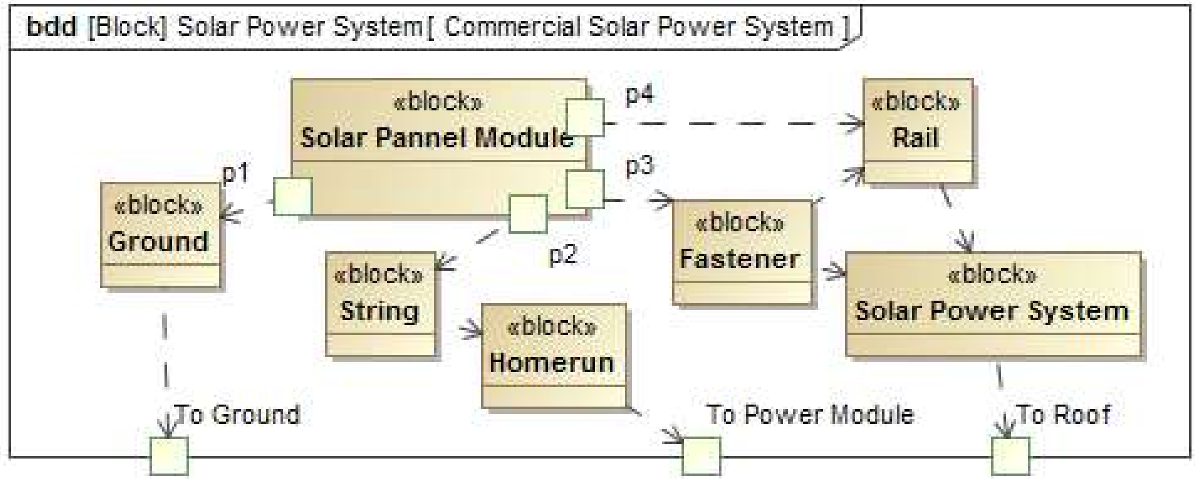


Figure 5.2.3.1 The block definition diagram of commercial solar power system

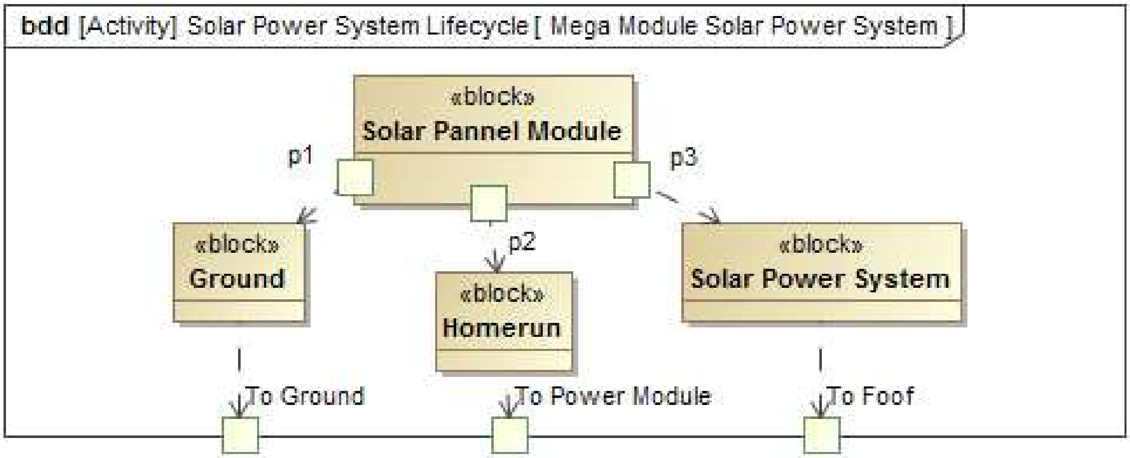


Figure 5.2.3.2 The block definition diagram of Mega Module solar power system

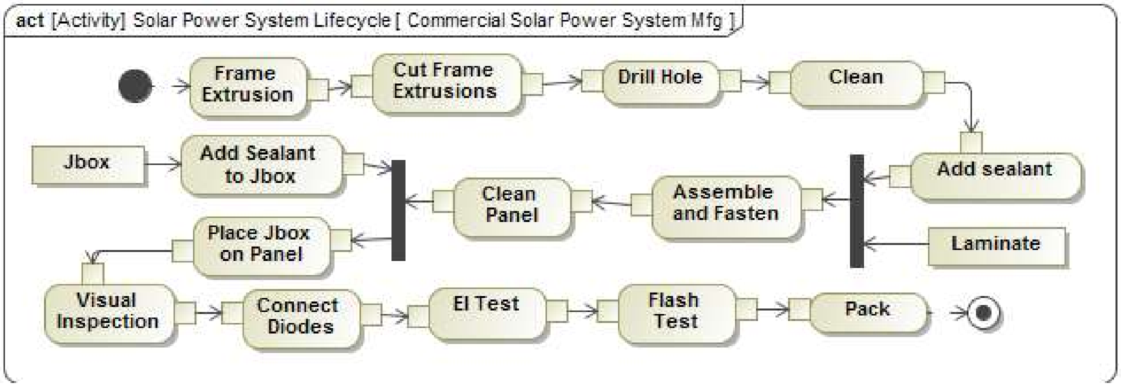


Figure 5.2.3.3 The activity diagram of manufacturing of commercial solar power system

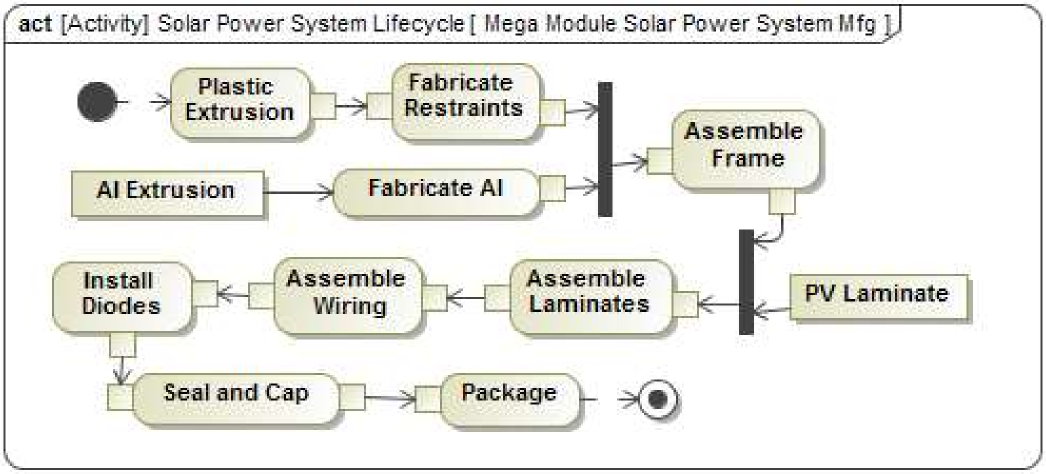


Figure 5.2.3.4 The activity diagram of manufacturing of Mega Module solar power system

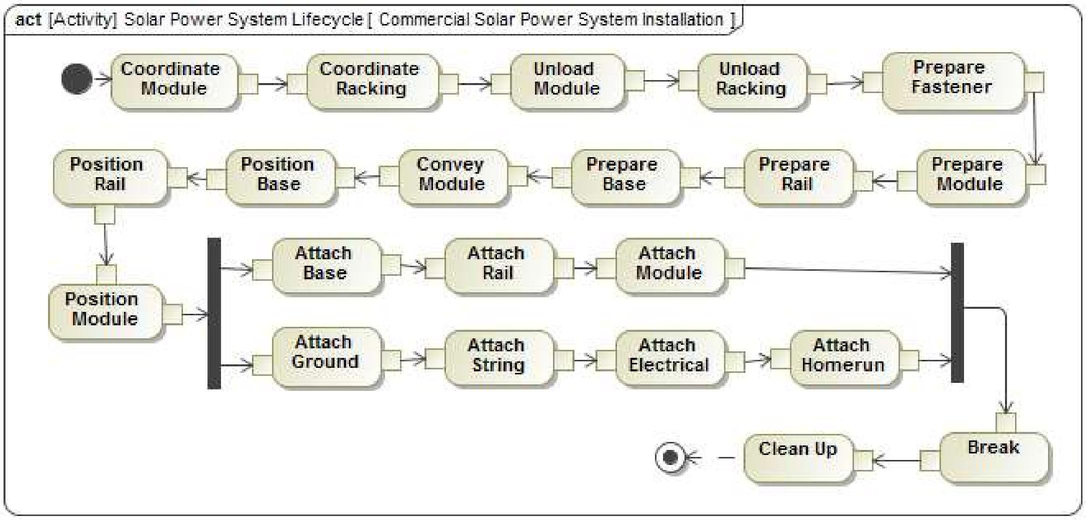


Figure 5.2.3.5 The activity diagram of installation of commercial solar power system

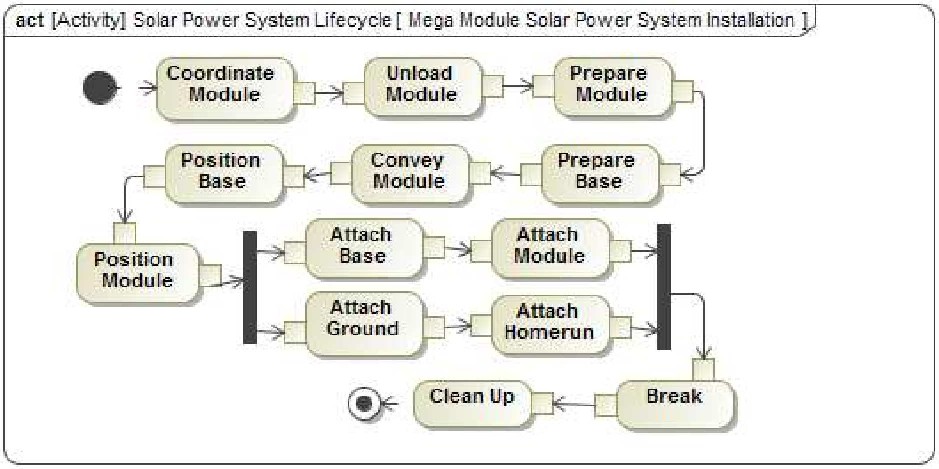


Figure 5.2.3.6 The activity diagram of Mega Module solar power system installation

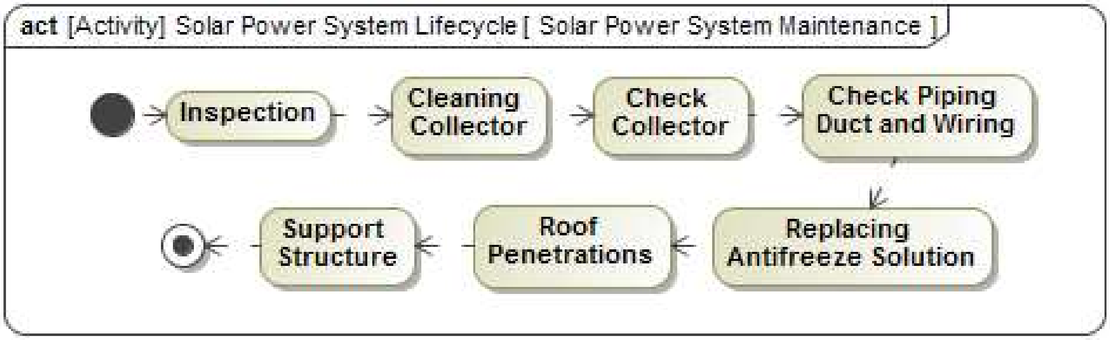


Figure 5.2.3.7 The activity diagram of scheduled maintenance of solar power system

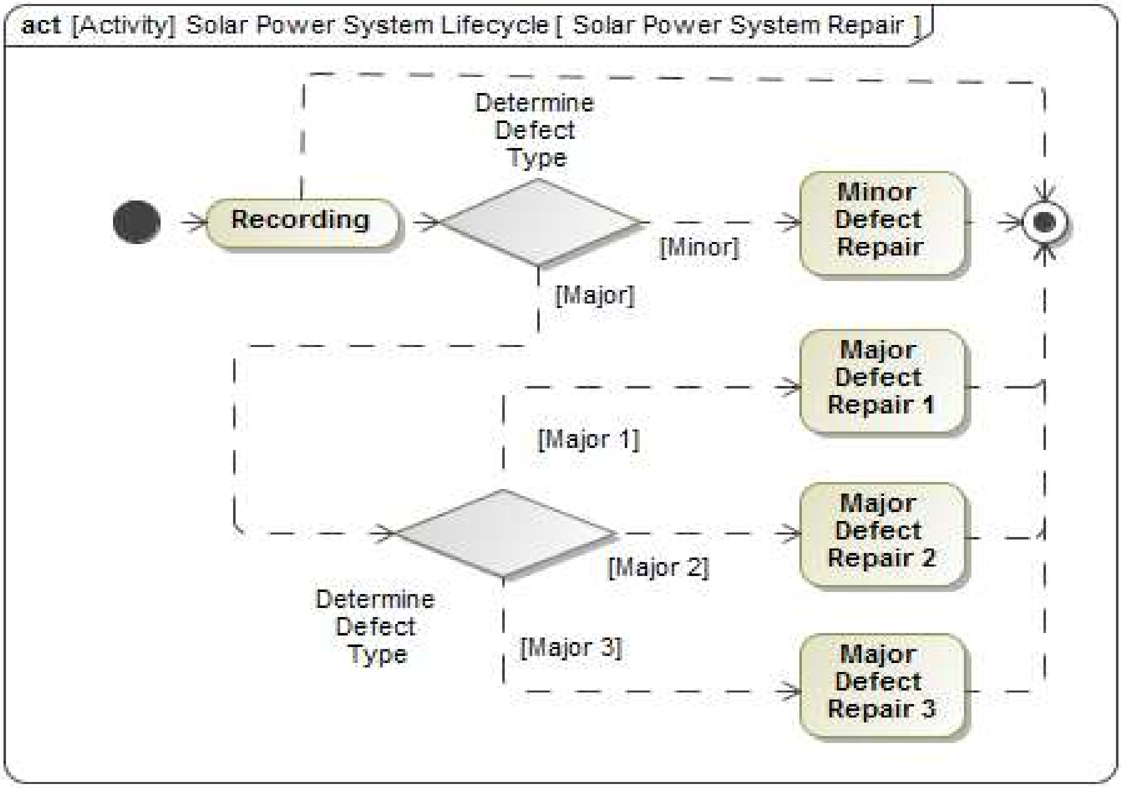


Figure 5.2.3.8 The activity diagram of repair maintenance solar power system

5.3 Verification and Validation

Describing systems is critical to communicating relevant information to stakeholders. System modeling is key to this communication. The method proposed utilized paper models for rapid and iterative modeling during data collection, and SysML for more complex model representations. Chapter 4 presented the general modeling and data collection method and then described its application to the MegaModule case study. The MegaModule and commercial systems were described using SysML. Paper models were not shown as they were used during the data collection process and their relevant information was contained in the SYSML models. SysML was shown to be an effective method of capturing the information for solar power systems because of its intelligent modeling features.

5.3. Summary

This section looks at methodology for modeling and data collection that can be used as part of the framework. It also introduces the MegaModule concept which will form the basis of the case study used to validate the methods discussed. The methodology consists of distinct activities; problem analysis, field investigation, data collection, as-is model construction. The MegaModule is introduced as part of the discussion on problem analysis. The problem is described as a comparison of the mega module lifecycle labor costs with the commercial system lifecycle labor costs, to determine if the design is an improvement. The next part of the methodology, field investigation is also discussed. The importance of this is described as a real world mapping of activities to support data collection. To support data collection, a data collection method used by the SIMPLE Bos team is presented as a viable method for the case study and framework. As-is models constructed in SysML are then presented as the final stage of this process.

CHAPTER 6

ARENA SIMULATION FOR LIFECYCLE COST ANALYSIS

An Arena simulation will help obtain estimated parameter values for each stage of the lifecycle. Data gathered through the methods outlined in the previous section can be used to identify probability distributions, which can be used as inputs to the Arena simulation. The SysML diagram can be used to create the structure of the arena model. This structure will connect each activity and help discover the interaction of each activity with activities occurring before and after, as well as provide insight into its role in the overall system performance. Through multiple cycles and replications, the design team can obtain an estimate of the design performance over each of the manufacturing, installation and maintenance stages.

6.1. Methodology

There are three stages to performing a discrete event simulation and obtaining parameters estimates to support design decisions. The first stage involves analyzing the input data and converting it into a form that can be used by the simulation model. During the second stage, the simulation model is built using previous modeling efforts as a guide. It is then run through a specific number of cycles and replications in order to produce the parameter estimates. Finally, the output is analyzed and used to draw conclusions about the design or make design decisions.

6.2. Input Analysis

Data collection is a messy process and requires some post processing to make it usable. In most onsite activities, there is considerable variation in the time it takes to perform a task. These variations can occur due to the skill of the operator, environmental conditions, the tools being used, etc. Often, the sequence of activities may also change.

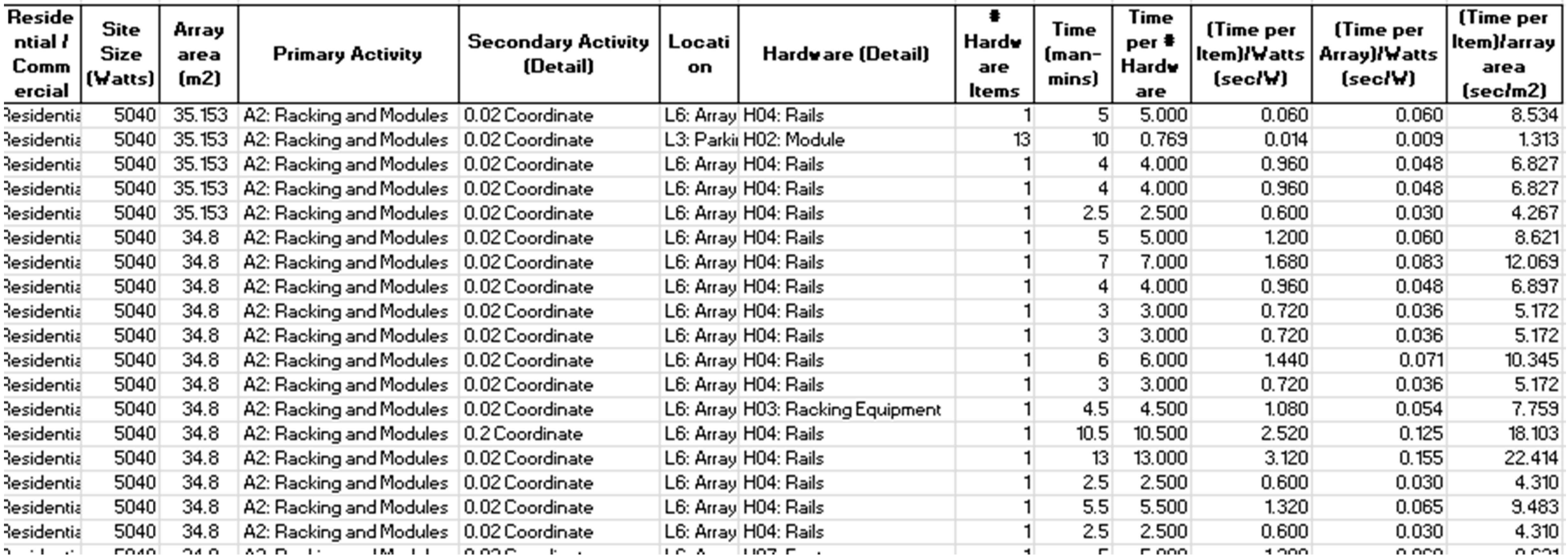
Therefore, the first step to creating a discrete event simulation is to review the data. The data should be first looked at to ensure that the sequence of events in the SysML model is consistent with that observed onsite. Any variations should be noted and the design team can decide whether the models should be changed to accommodate the variations. Once this is accomplished the data should be analyzed for fit with well-known probability distributions, or configured for direct input into the model.

Fitting to a probability distribution can be done in a variety of ways. Arena has an input analyzer included, and programs like MATLAB, Fortran, and R have functions that help check for fit. These programs typically utilize a process that involves comparing the data to standard probability distributions, tweaking the distributions and then checking for fit. The program utilizes goodness of fit tests which may include the χ^2 goodness of fit test or the Kolmogorov-Smirnov goodness of fit test. The design team can use the results of the input analysis to pick the appropriate distribution with appropriate parameters. Thus can be input into the Arena block by selecting the distribution name and adding parameter values in the block properties.

6.2.1. Data input

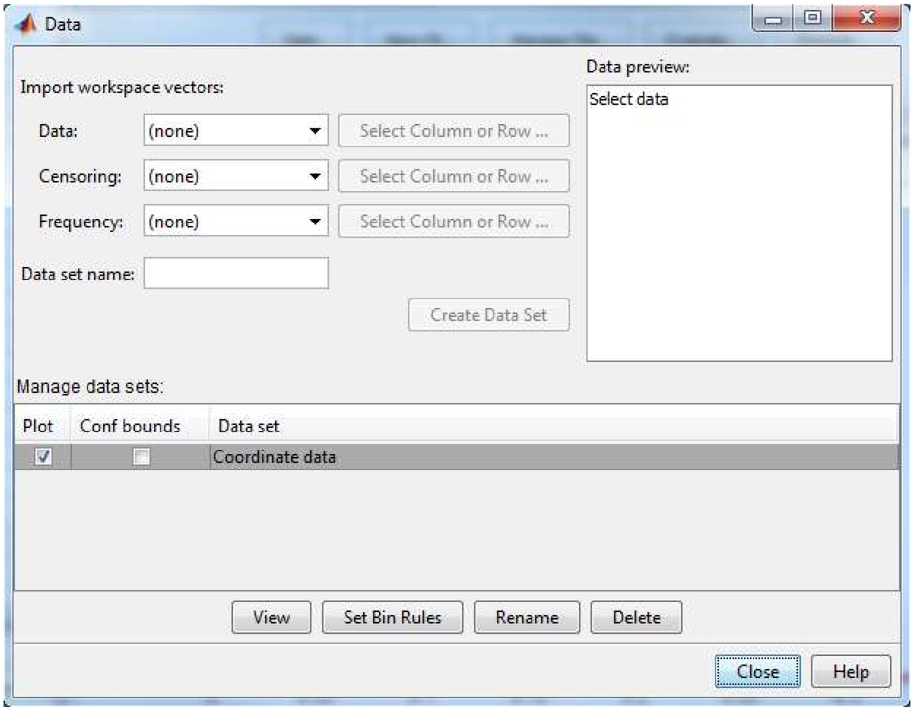
Input data, provided by GTRI for installation activities, was analyzed using MATLAB's dfittool. In this section, the steps used to analyze the data will be described for the base preparation activity, which can be considered a representative installation activity.

The data for the installation was collected by the GTRI team and was captured in an excel file. The format of the excel file with the data is shown in Figure 6.2.1.1. The seconds/watt version of the data was first imported into the MATLAB workspace. The input into the dfittool as shown in Figure 7.2.1.1. Using the "New Fit" dialogue, a distribution was automatically fitted to the data and the distribution parameters were noted. Several distributions were used and then compared to determine best fit.



Residential / Commercial	Site Size (Watts)	Array area (m2)	Primary Activity	Secondary Activity (Detail)	Location	Hardware (Detail)	# Hardware Items	Time (man-mins)	Time per # Hardware	(Time per Item)/Watts (sec/W)	(Time per Array)/Watts (sec/W)	(Time per Item)/array area (sec/m2)
Residentia	5040	35.153	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	5	5.000	0.060	0.060	8.534
Residentia	5040	35.153	A2: Racking and Modules	0.02 Coordinate	L3: Parki	H02: Module	13	10	0.769	0.014	0.009	1.313
Residentia	5040	35.153	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	4	4.000	0.960	0.048	6.827
Residentia	5040	35.153	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	4	4.000	0.960	0.048	6.827
Residentia	5040	35.153	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	2.5	2.500	0.600	0.030	4.267
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	5	5.000	1.200	0.060	8.621
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	7	7.000	1.680	0.083	12.069
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	4	4.000	0.960	0.048	6.897
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	3	3.000	0.720	0.036	5.172
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	3	3.000	0.720	0.036	5.172
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	6	6.000	1.440	0.071	10.345
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	3	3.000	0.720	0.036	5.172
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H03: Racking Equipment	1	4.5	4.500	1.080	0.054	7.759
Residentia	5040	34.8	A2: Racking and Modules	0.2 Coordinate	L6: Array	H04: Rails	1	10.5	10.500	2.520	0.125	18.103
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	13	13.000	3.120	0.155	22.414
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	2.5	2.500	0.600	0.030	4.310
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	5.5	5.500	1.320	0.065	9.483
Residentia	5040	34.8	A2: Racking and Modules	0.02 Coordinate	L6: Array	H04: Rails	1	2.5	2.500	0.600	0.030	4.310

Figure 6.2.1.1 Excerpt of excel file containing time study data



Import workspace vectors:

Data: (none)

Censoring: (none)

Frequency: (none)

Data set name:

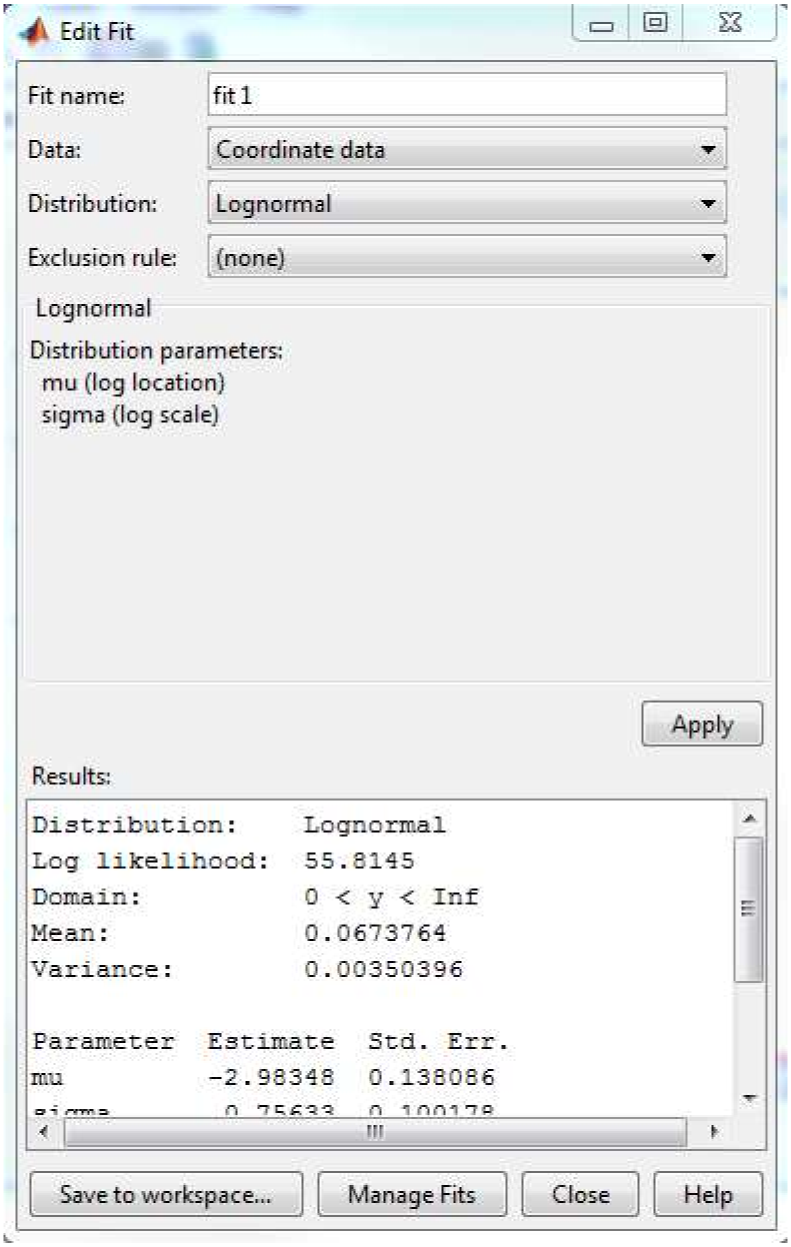
Data preview:

Select data

Manage data sets:

Plot	Conf bounds	Data set
☑	☐	Coordinate data

Figure 6.2.1.2 MATLAB dfittool data input



Fit name: fit 1

Data: Coordinate data

Distribution: Lognormal

Exclusion rule: (none)

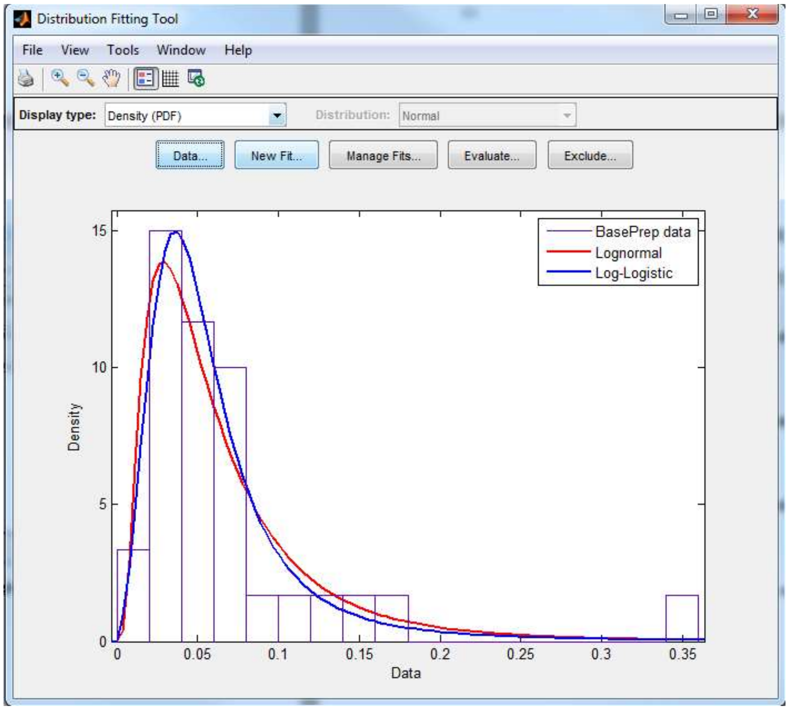
Lognormal

Distribution parameters:
mu (log location)
sigma (log scale)

```
Distribution:    Lognormal
Log likelihood:  55.8145
Domain:          0 < y < Inf
Mean:            0.0673764
Variance:        0.00350396

Parameter  Estimate  Std. Err.
mu         -2.98348  0.138086
sigma       0.75633  0.100178
```

Figure 6.2.1.3 Distribution fitting dialogue with results



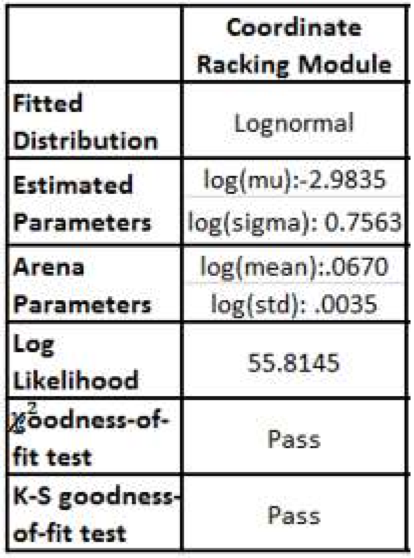
Display type: Density (PDF)

Distribution: Normal

Figure 6.2.1.4 Fitted Lognormal and Log-Logistic distributions

After fitting the distribution, the fit was checked using goodness of fit tests.

Table 6.2.1.1 Distribution parameters and goodness of fit



	Coordinate Racking Module
Fitted Distribution	Lognormal
Estimated Parameters	log(mu):-2.9835 log(sigma): 0.7563
Arena Parameters	log(mean):.0670 log(std): .0035
Log Likelihood	55.8145
χ^2 goodness-of-fit test	Pass
K-S goodness-of-fit test	Pass

6.3. Arena Model

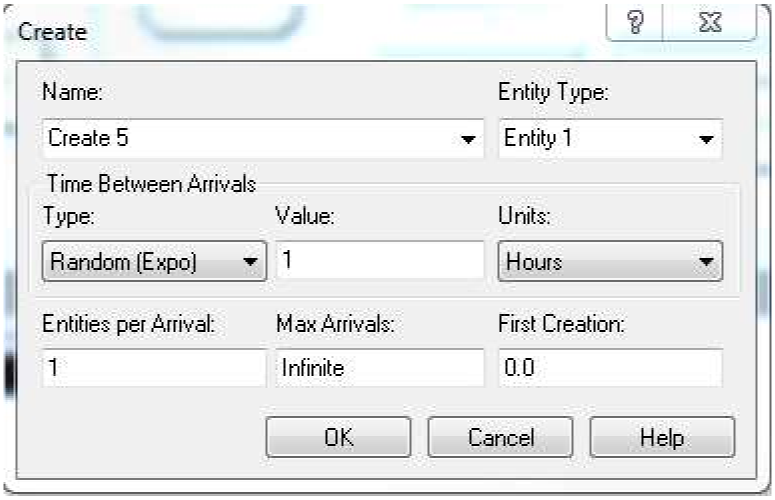
Creation of the Arena Model is made easy by the SysML model and input analysis. The Arena model process blocks can be configured identically to the SysML activity diagrams. The processing times for each block can be input using the distributions identified during input analysis. Any unknown data can be estimated by the design team and input in lieu of distributions generated from actual data. Entity generation strategies may be the only departure from the SysML layout. Generating and discarding entities that drive the system behavior requires some thought on the part of the simulation team. They must be able to configure the layout to ensure that the entity pathways match expected system behavior.

6.3.1. Creating the Arena Models

The Arena diagram consists of entities and various specialized blocks that create, process, terminate, combine, etc. the entities. Entities are the driving force behind events and block actions in the diagram. Entities are used differently in each representation to try and accurately capture the sequence of events, many of which are not sequential.

6.3.1.1. Entity Creation

Entities are created using the ‘Create’ block. The parameters of creation are set in the entity creation dialogue box, shown in Figure 7.3.1.1. In this study, the model was kept simple by using the standard entity type in the installation and maintenance models, but due to the need for concurrent process in the manufacturing model, representative entity types were created. The time between each arrival was also set at a standard Exponential Distribution. In the manufacturing models, the mean was set at 1 hour, in the installation and maintenance models it was set at 1 day. In all models the number of arrivals was set to be ‘Infinite’.



Name: Create 5
Entity Type: Entity 1
Time Between Arrivals
Type: Random (Expo)
Value: 1
Units: Hours
Entities per Arrival: 1
Max Arrivals: Infinite
First Creation: 0.0

Figure 6.2.1.4 Example Entity Creation Parameters

6.3.1.2. Entity Splitting

The manufacturing models differ from the installation and maintenance models in that many parts are prepared concurrently before they are assembled into a final product. Instead of creating separate entities for each part, one entity was created and split to represent the concurrent production paths. The entities were then combined when the production paths converged into an assembly action. Figure 6.3.1.2. illustrates the splitting of the parent entity into entities representing the polymeric restraints and the aluminum frame components, both of which follow concurrent fabrication parts before being assembled together.

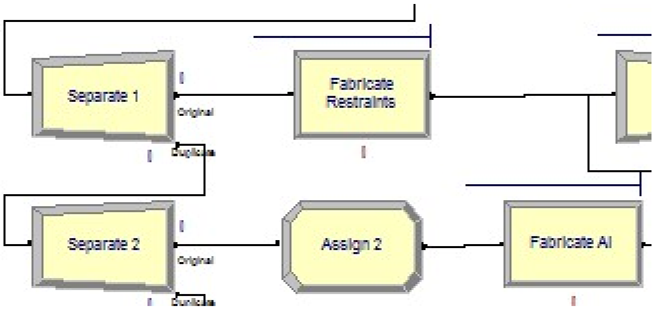
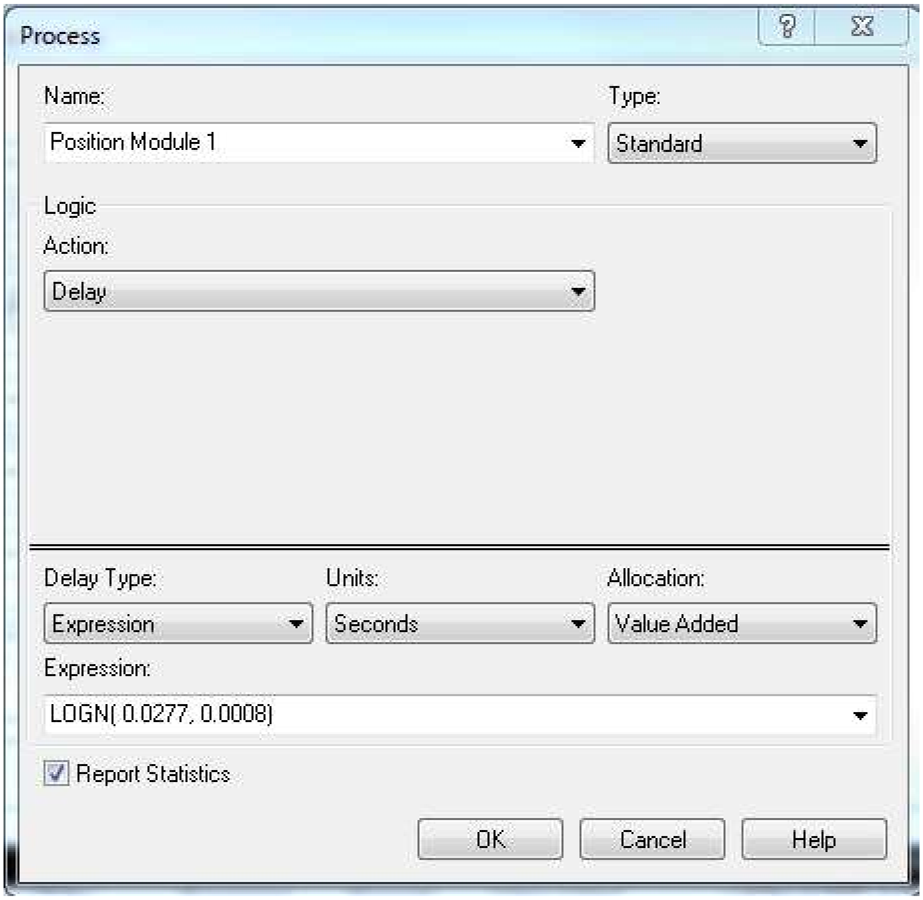


Figure 6.3.1.2.1 Entities being split in the MegaModule manufacturing sequence

6.3.1.3. Processes

Process blocks are used to represent the various processes occurring. Process blocks are used exactly the same way in each model, but with different distributions and distribution parameters. For activities where data was available, distributions were fitted and to the data and the result was used as an input to the process block. Figure 6.3.1.3.1. shows the position module 1 activity, which uses a Lognormal distribution with specific parameters for mu and sigma. The distribution provides a delay time for each entity, thus representing the time taken to perform the activity. For activities without actual data, triangular distributions with estimated mean, max, and min parameters were used. Figure 6.3.1.3.2. shows the use of an estimated triangular distribution.



Name: Position Module 1

Type: Standard

Logic

Action: Delay

Delay Type: Expression

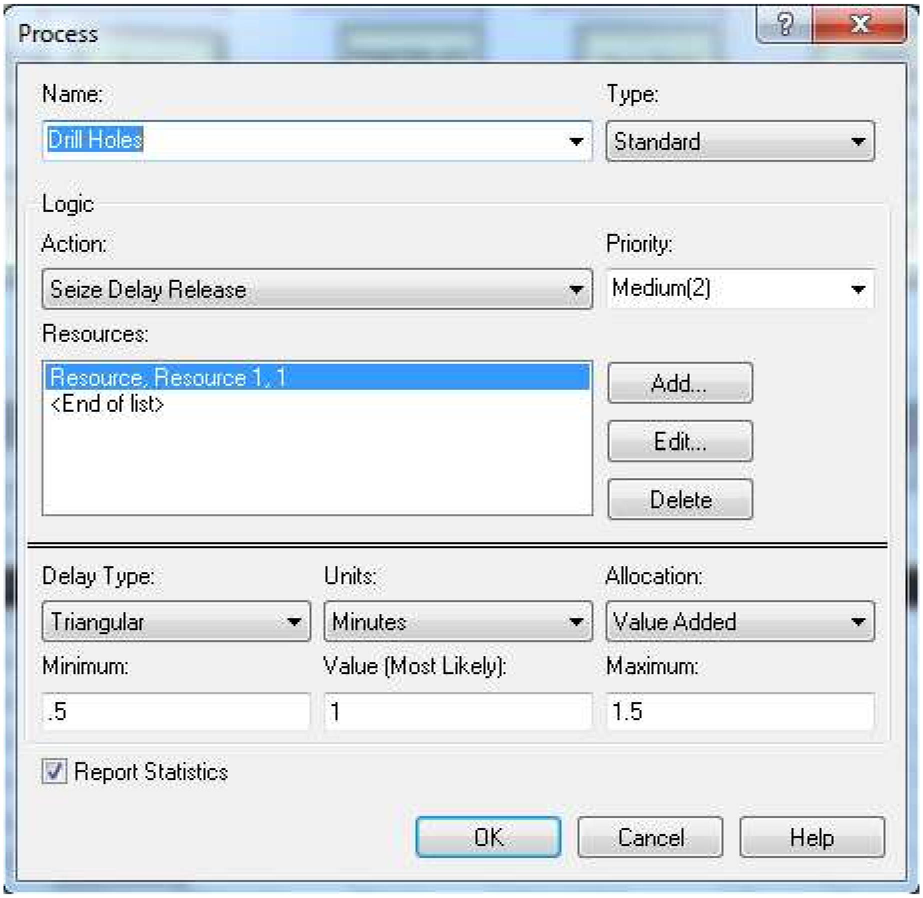
Units: Seconds

Allocation: Value Added

Expression: LOGN(0.0277, 0.0008)

☑ Report Statistics

Figure 6.3.1.3.1 Process block dialogue for an Installation activity with fitted distribution



Name: Drill Holes
Type: Standard

Logic

Action: Seize Delay Release
Priority: Medium(2)

Resources:
Resource, Resource 1, 1
<End of list>

Delay Type: Triangular
Units: Minutes
Allocation: Value Added

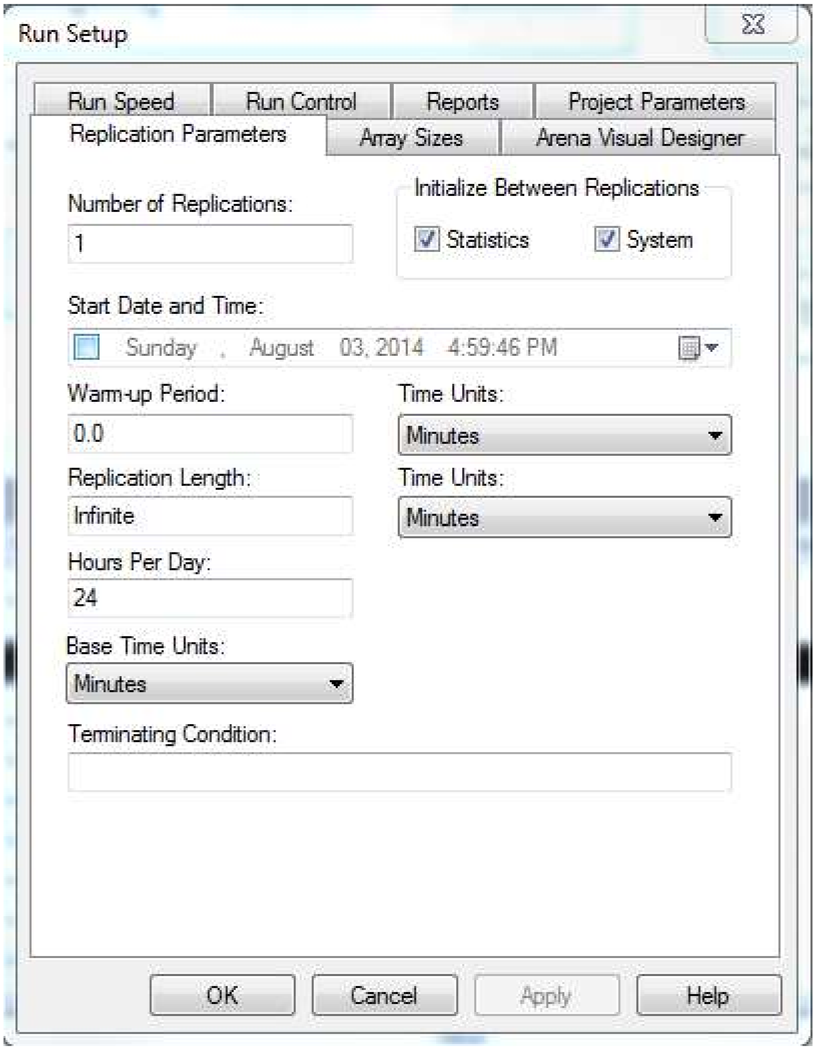
Minimum: .5
Value (Most Likely): 1
Maximum: 1.5

☑ Report Statistics

Figure 6.3.1.3.2. Process block dialogue for an Installation activity with estimated distribution

6.3.1.4. Setting up the Experiment

To reduce computation time, each experiment was run only once, so the replication parameter was set to 1. Default setup parameters were used, but the time units were changed based on the type of model. Replication length time units for manufacturing models were set as infinite minutes, for installation and maintenance they were set as 3000 days. The manufacturing replication length could be set as infinite since the experiment length was controlled by the number of modules produced by limiting the number of entities that were created in the experiment. An example of a run setup is shown in Figure 6.3.1.4.1.



Number of Replications: 1

Initialize Between Replications: ☑ Statistics ☑ System

Start Date and Time: ☐ Sunday , August 03, 2014 4:59:46 PM

Warm-up Period: 0.0
Time Units: Minutes

Replication Length: Infinite
Time Units: Minutes

Hours Per Day: 24

Base Time Units: Minutes

Terminating Condition:

Figure 6.3.1.4.1 Run set up for commercial system manufacturing

6.4. MegaModule Case Study

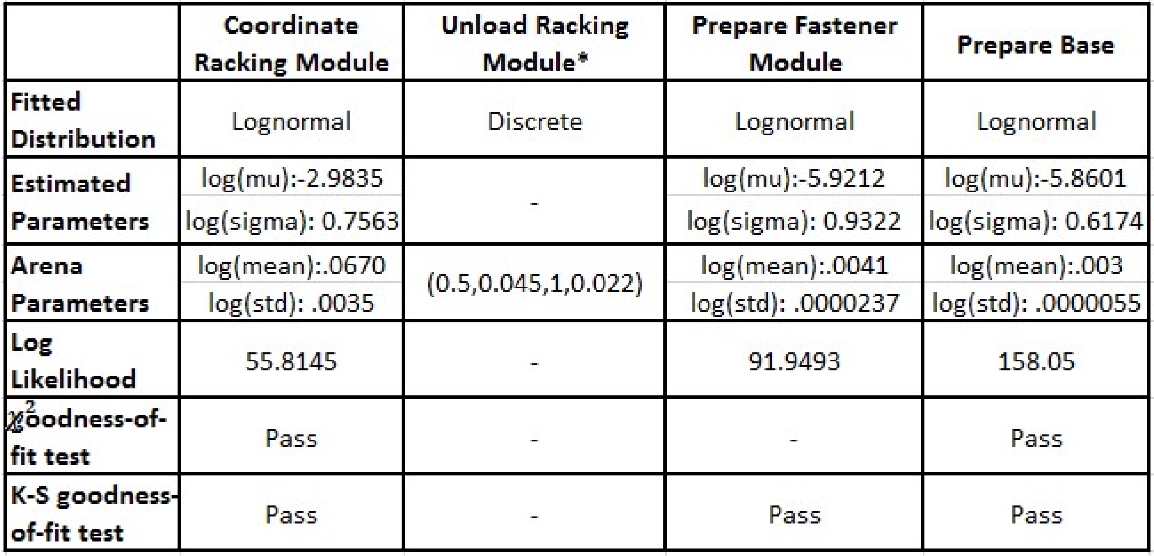
6.4.1. Input Analysis

Data collection is takes a significant effort to accomplish since it requires many individuals observing activities over long periods and in different settings. The GTRI research group which was responsible for developing the MegaModule had collected data for the installation stage of the commercial residential system. However, there was no data collected for the manufacturing and maintenance stages. As a result, the design team decided to estimate the distributions for each activity that was known to occur in the stages for which data was not available. The same approach was taken for MegaModule data collection since it is a conceptual design and has yet to be manufactured. Therefore the input analysis below was conducted for the installation data of the commercial residential system.

There was significant variation in the types of systems installed, so that the data were combined into general activity categories that were observed in the installation phase. These categories consist of Racking and Modules, Electric and Wire, and Non-production. Each category contains secondary activities, such as preparation, coordination, convey, position, etc. Input analysis was then conducted using the dfittool in Matlab. Among all the fitted distributions, only the best distribution was selected based on three criteria, including Log Likelihood, Chi-square goodness-of-fit test, and K-S goodness-of-fit test, except when the best distribution is not available in Arena. In such a circumstance, the next best distribution was selected. However, for some of the activities, continuous distributions seem not good enough for them due to lack of data, empirical discrete distributions were estimated.

Racking and Modules: In the activity of racking modules, 11 secondary activities were identified for input analysis. They are summarized in Tables 6.4.1.1. to 6.4.1.3.

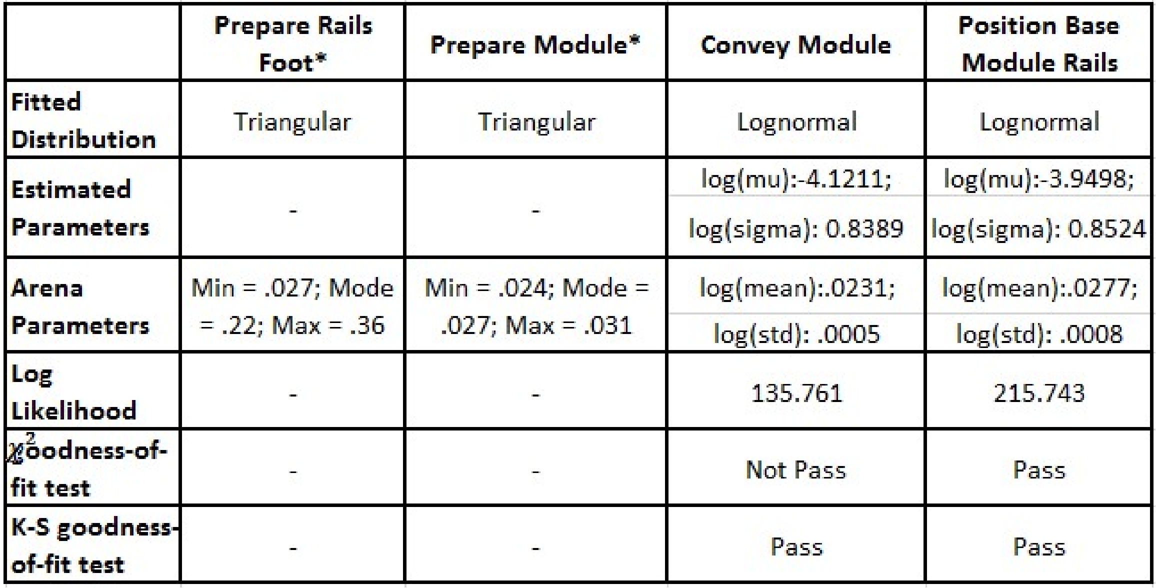
Table 6.4.1.1 Input analysis for secondary activities involved in Racking and Modules



	Coordinate Racking Module	Unload Racking Module*	Prepare Fastener Module	Prepare Base
Fitted Distribution	Lognormal	Discrete	Lognormal	Lognormal
Estimated Parameters	log(mu):-2.9835 log(sigma): 0.7563	-	log(mu):-5.9212 log(sigma): 0.9322	log(mu):-5.8601 log(sigma): 0.6174
Arena Parameters	log(mean):.0670 log(std): .0035	(0.5,0.045,1,0.022)	log(mean):.0041 log(std): .0000237	log(mean):.003 log(std): .0000055
Log Likelihood	55.8145	-	91.9493	158.05
χ^2 goodness-of-fit test	Pass	-	-	Pass
K-S goodness-of-fit test	Pass	-	Pass	Pass

*secondary activities fitted empirically

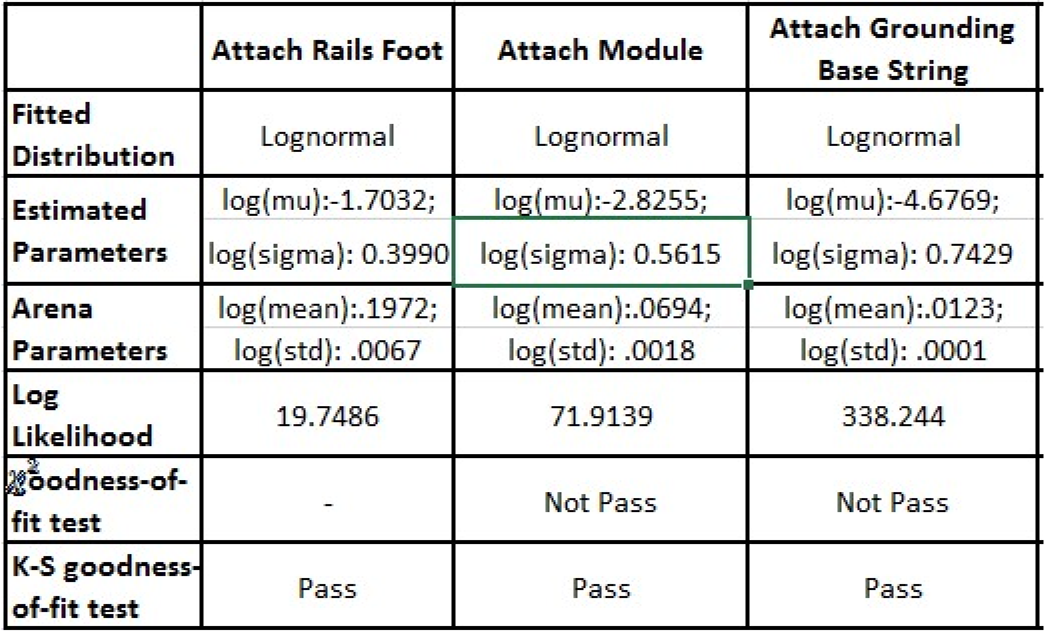
Table 6.4.1.2 Input analysis for secondary activities involved in Racking and Modules (continued)



	Prepare Rails Foot*	Prepare Module*	Convey Module	Position Base Module Rails
Fitted Distribution	Triangular	Triangular	Lognormal	Lognormal
Estimated Parameters	-	-	log(mu):-4.1211; log(sigma): 0.8389	log(mu):-3.9498; log(sigma): 0.8524
Arena Parameters	Min = .027; Mode = .22; Max = .36	Min = .024; Mode = .027; Max = .031	log(mean):.0231; log(std): .0005	log(mean):.0277; log(std): .0008
Log Likelihood	-	-	135.761	215.743
χ^2 goodness-of-fit test	-	-	Not Pass	Pass
K-S goodness-of-fit test	-	-	Pass	Pass

*secondary activities fitted empirically

Table 6.4.1.3 Input analysis for secondary activities involved in Racking and Modules (continued)



	Attach Rails Foot	**Attach Module**	**Attach Grounding Base String**
Fitted Distribution	Lognormal	Lognormal	Lognormal
Estimated Parameters	log(mu):-1.7032; log(sigma): 0.3990	log(mu):-2.8255; log(sigma): 0.5615	log(mu):-4.6769; log(sigma): 0.7429
Arena Parameters	log(mean):.1972; log(std): .0067	log(mean):.0694; log(std): .0018	log(mean):.0123; log(std): .0001
Log Likelihood	19.7486	71.9139	338.244
χ^2 goodness-of-fit test	-	Not Pass	Not Pass
K-S goodness-of-fit test	Pass	Pass	Pass

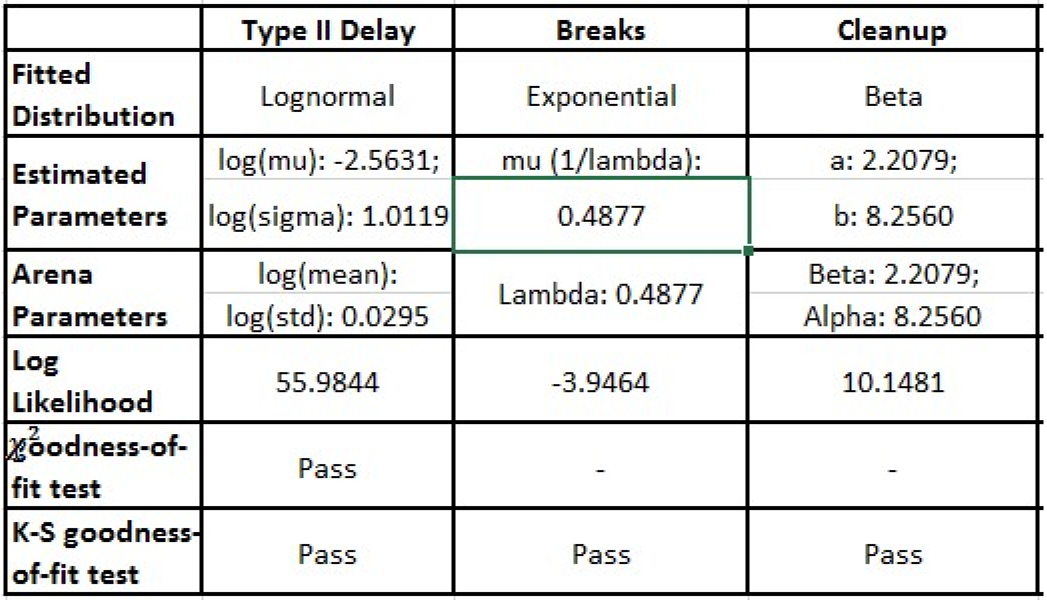
Electrical and Wire Management: The electrical and wire management mainly has four secondary activities, namely attaching strings, attaching electrical equipment, attaching homerun, and attaching grounding. Other secondary activities with few data were excluded for input analysis. The summary of input analysis of secondary activities involved is shown in Table 6.4.1.4.

Table 6.4.1.4 Input analysis for secondary activities involved in Electrical and Wire Management

	Attach Strings	Attach Electrical Equipment	Attach Grounding	Attach Homerun
Fitted Distribution	Weibull	Lognormal	Weibull	Weibull
Estimated Parameters	a:0.8745; b:1.9304	log(mu):-1.1114; log(sigma): 0.4403	a:0.0866; b:3.8851	a:1.8519; b:1.6216
Arena Parameters	Beta:0.8745; Alpha:1.9304	log(mean): 0.3626; log(std): 0.0281	Beta:0.0866; Alpha:3.8851	Beta:1.8519; Alpha:1.6216
Log Likelihood	-15.1895	5.11592	40.167	-16.3908
χ^2 goodness-of-fit test	Pass	-	-	-
K-S goodness-of-fit test	Pass	Pass	Pass	Pass

(3) Non-production: The non-production activities include three secondary activities, namely Type II Delay, breaks, and cleanup. The summary of input analysis of them is presented in Table 3. Since only a few data were collected for breaks and cleanup, only K-S test was performed to evaluate their goodness-of-fit.

Table 6.4.1.5 Input analysis for secondary activities involved in Non-production activities



	Type II Delay	**Breaks**	**Cleanup**
Fitted Distribution	Lognormal	Exponential	Beta
Estimated Parameters	log(mu): -2.5631; log(sigma): 1.0119	mu (1/lambda): 0.4877	a: 2.2079; b: 8.2560
Arena Parameters	log(mean): log(std): 0.0295	Lambda: 0.4877	Beta: 2.2079; Alpha: 8.2560
Log Likelihood	55.9844	-3.9464	10.1481
χ^2 goodness-of-fit test	Pass	-	-
K-S goodness-of-fit test	Pass	Pass	Pass

6.4.2. Arena Model

Arena models were created for both the commercial and Mega Module systems. A separate model was created for each phase due to differences in time scale for the manufacturing (i.e., minutes), installation (i.e., hours), and maintenance (i.e., years) phases, respectively.

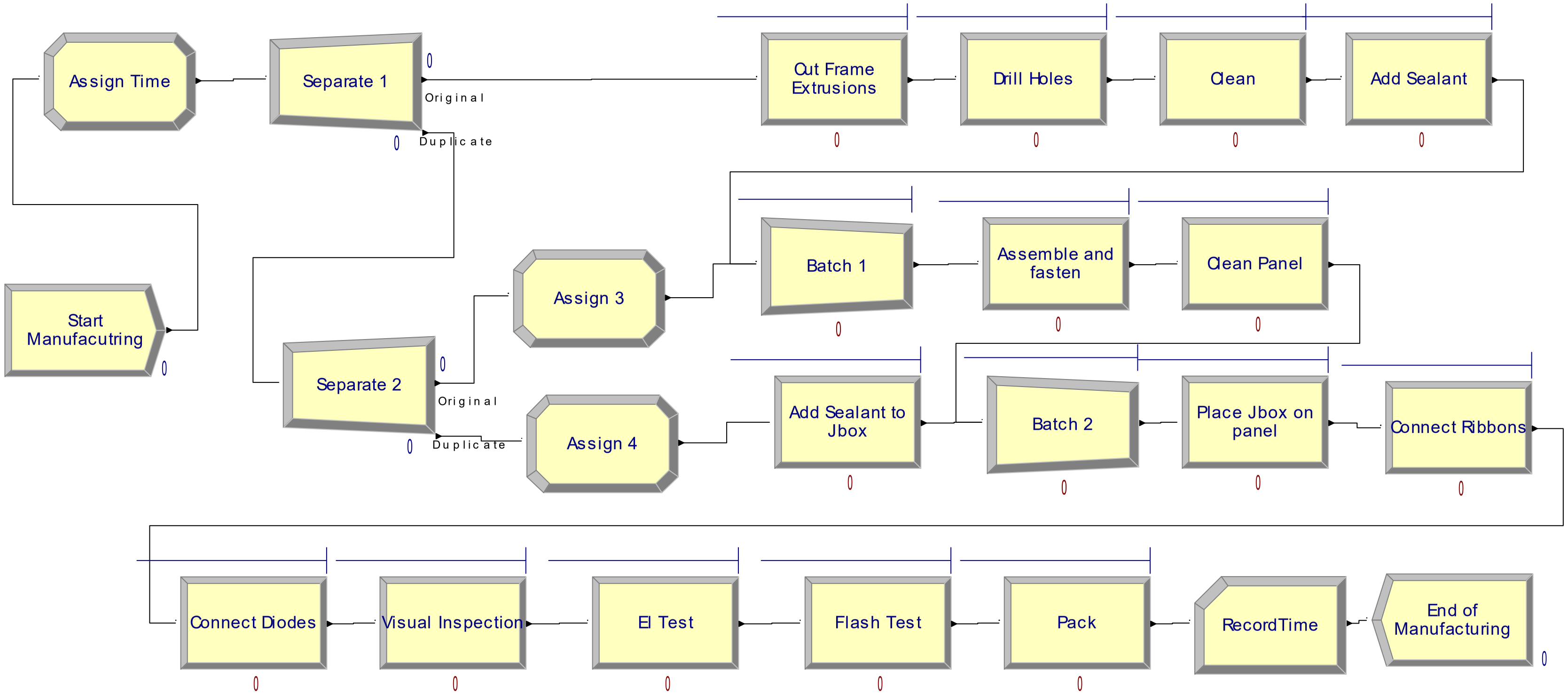


Figure 6.4.2.1 Arena model of manufacturing phase for the commercial system

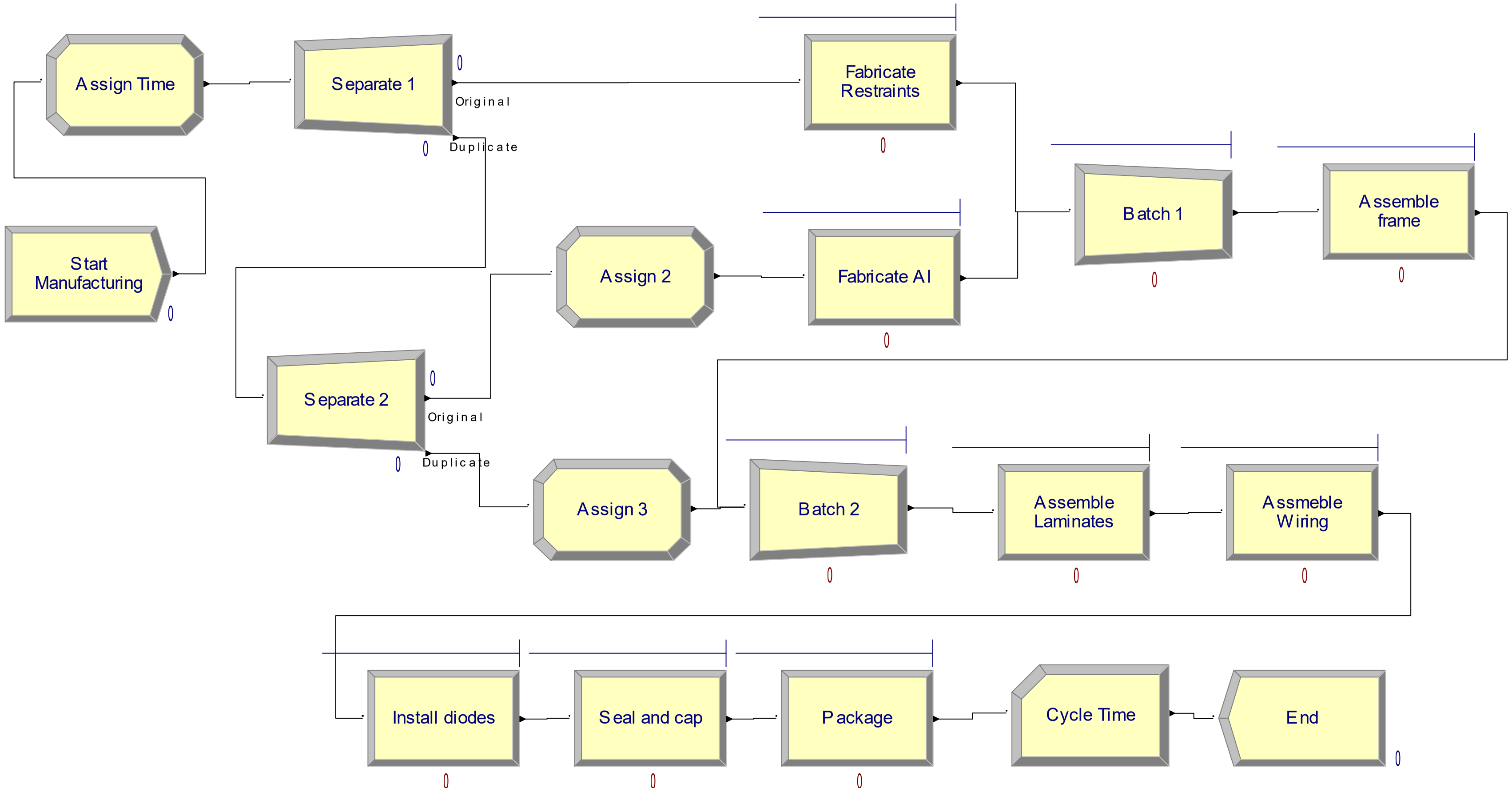


Figure 6.4.2.2 Arena model of manufacturing phase for the MegaModule

Each of the manufacturing models had a single source of entities to simplify batching. Copies of the initial entity were created using separation blocks and were used to represent the major component categories. Entities were then batched using combine blocks to represent their addition to the module assembly. At the end of the production run, the entity batches were discarded in their entirety. Each processing step that was applied to the entities used estimated distributions to model the variability of processing time in the process. For both the commercial and Mega Module systems, there are three distinct sub-phases; frame fabrication and assembly, panel and frame assembly, and electrical component assembly. The commercial system has fewer processing blocks than the Mega Module. However, their processing times were much less, due to the higher complexity fabrication and assembly of the Mega Module.

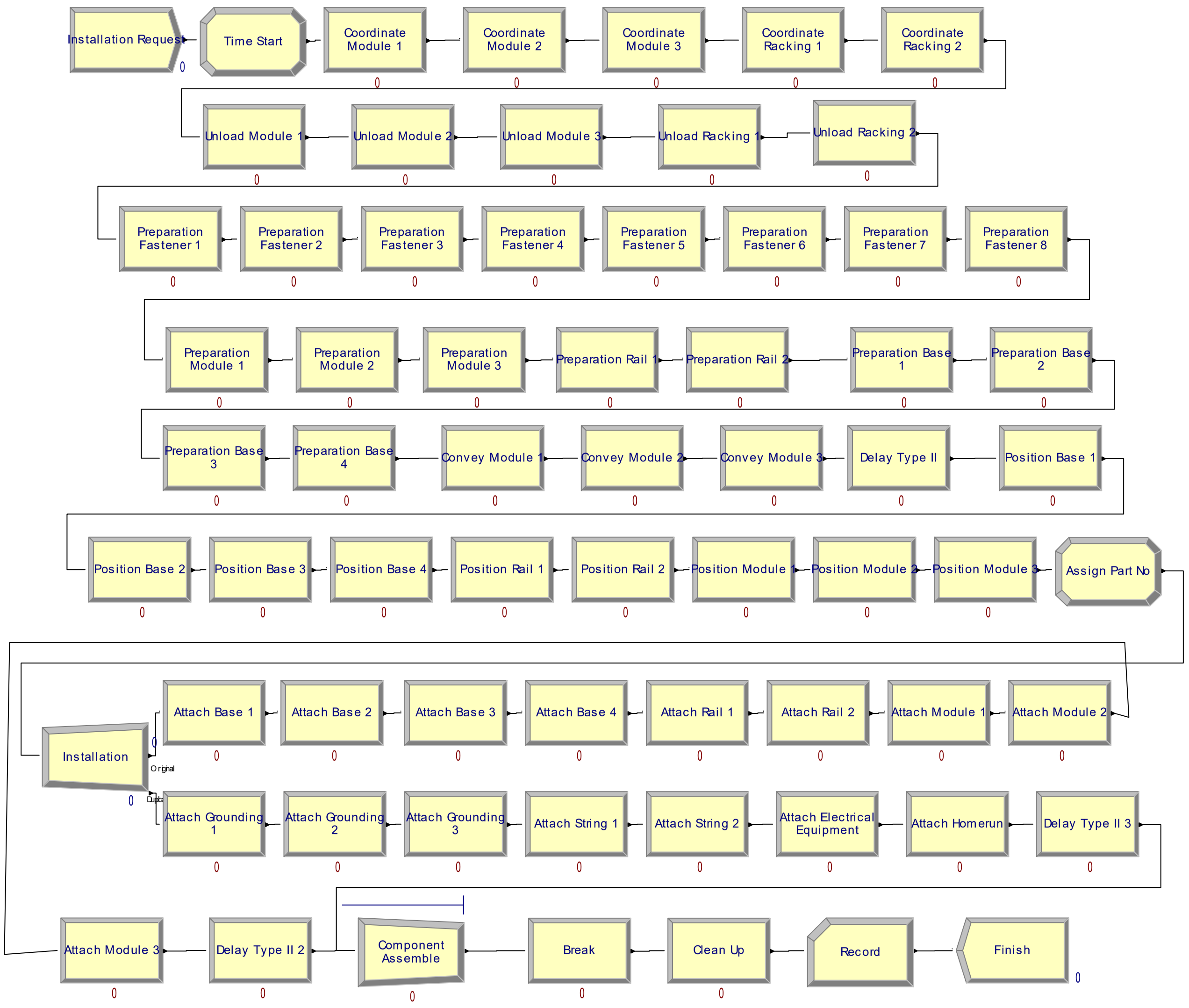


Figure 6.4.2.3 **Arena model of installation phase for the commercial system**

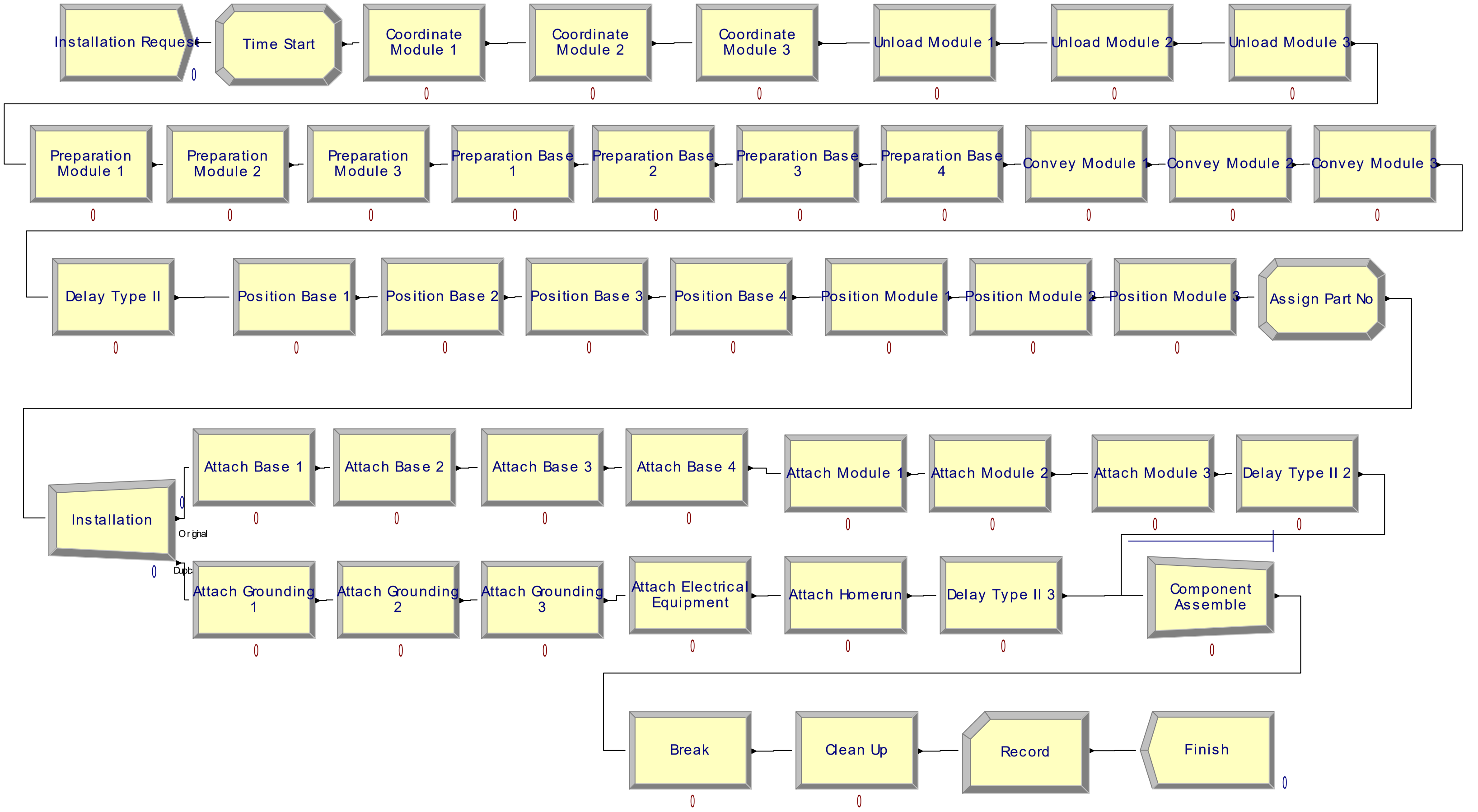


Figure 6.4.2.4 Arena model of installation phase for the Mega Module system

The installation process has three main parts; racking and mounting system installation, electrical system installation, and non-productive activities. The process of commercial system installation was built based on the data collected from the field study. Processing time distributions were identified through the input analysis described earlier. As the Mega Module system is still in prototype stage, the distributions were obtained based on the prototype installation with similar installation procedure of the commercial system. From the comparison of the two following Arena models, we can see the Mega Module system has much fewer process blocks and that should lead to a significant difference in the simulation result. The given standard commercial system has 3 solar modules, 2 rails, 4 bases and 8 fasteners sets, so that the model was built to ensure the ratio of different components are constant.

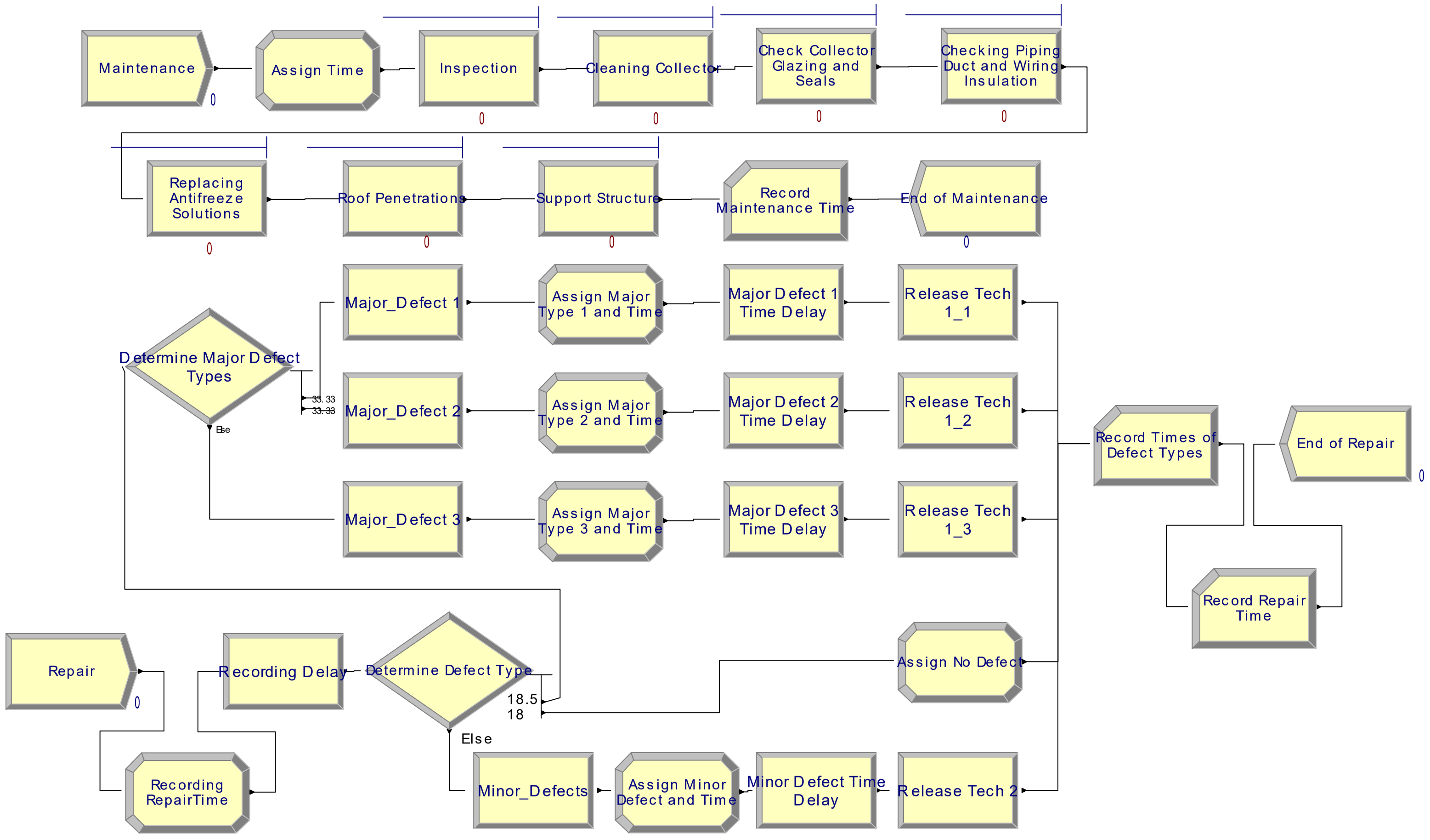
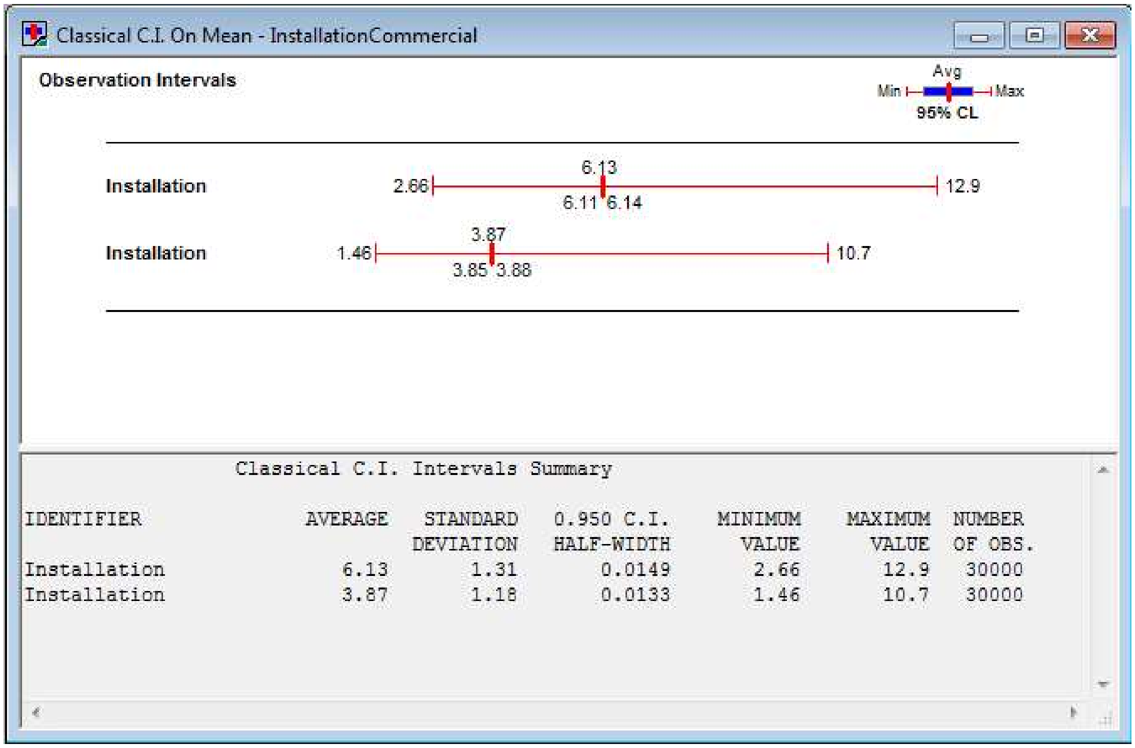


Figure 6.4.2.5 Arena model of maintenance phase for both the commercial and Mega Module system (only processing times are different)

The major difference between the commercial system and the Mega Module system is the repair time, which is similar to the time to install depending on the particular defects in the system. We assume that unsafe wiring is related to the activity of electrical and wire management. The delay is the aggregation of the four secondary activities involved, broken panel is related to all the activities involved in the installation process, and faulty inverter is related to the secondary activities in racking and module. For minor defects, the repair time is around 30% to 40% of major defects. According to these assumptions, we can determine the appropriate distributions for each delay in terms of major defects and minor defects.

6.4.3. Output Analysis

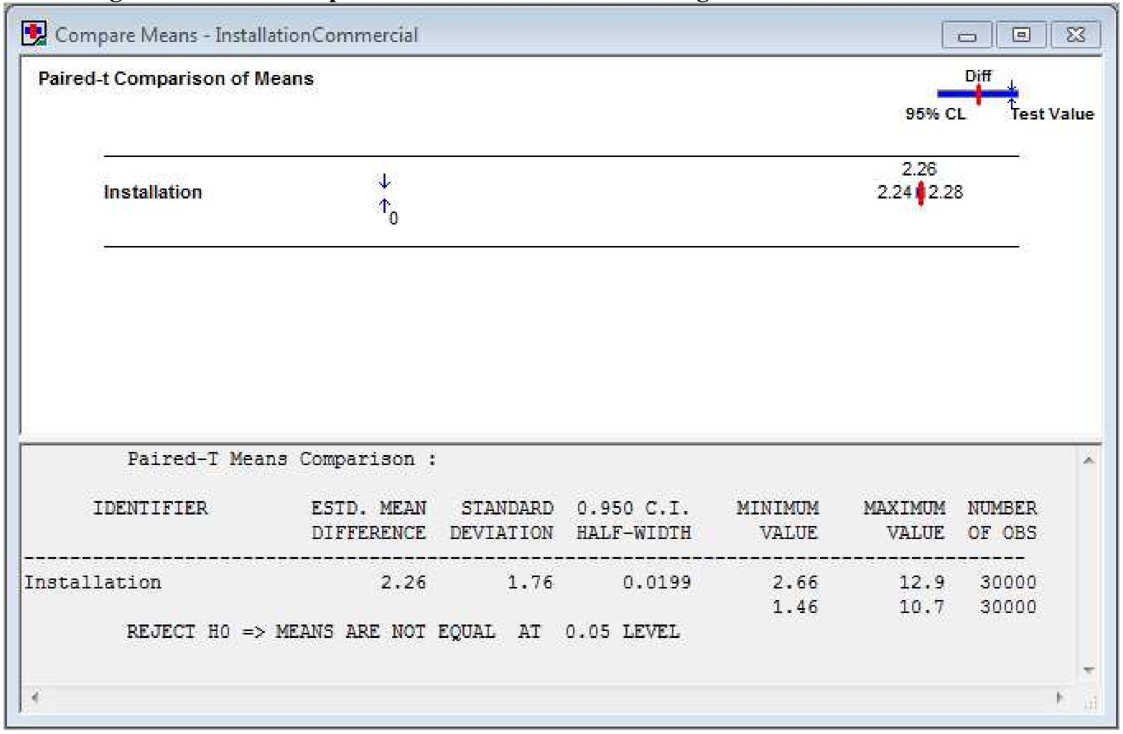
Output analysis of the simulation data was performed using Arena’s output analyzer. This is a separate tool provided as part of the Arena toolkit. The output analyzer was used to calculate the classical mean and confidence intervals, which were illustrated using box plots. The means were then compared using the compare means tool, which utilized a paired t test. The figures below show the results of the steps described above, for the installation of the commercial and mega module systems.



```
                 Classical C.I. Intervals Summary

IDENTIFIER                AVERAGE   STANDARD   0.950 C.I.    MINIMUM     MAXIMUM  NUMBER
                                   DEVIATION   HALF-WIDTH      VALUE       VALUE  OF OBS.
Installation                 6.13       1.31       0.0149       2.66        12.9   30000
Installation                 3.87       1.18       0.0133       1.46        10.7   30000
```

Figure 6.4.3.1 Box plots for the commercial and mega module installation labor time



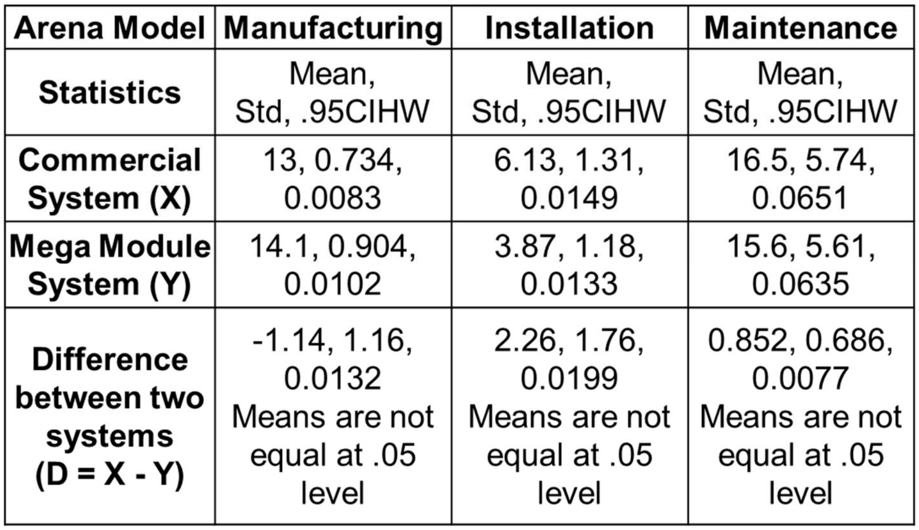
```
        Paired-T Means Comparison :

     IDENTIFIER          ESTD. MEAN   STANDARD  0.950 C.I.    MINIMUM     MAXIMUM  NUMBER
                         DIFFERENCE  DEVIATION  HALF-WIDTH      VALUE       VALUE  OF OBS
------------------------------------------------------------------------------------------
Installation                   2.26       1.76      0.0199       2.66        12.9   30000
                                                                 1.46        10.7   30000
        REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
```

Figure 6.4.3.2 Paired t –test results comparing means commercial and mega module installation labor time means

6.4.4. Data Interpretation

Table 6.4.4.1 Summary of simulation results



Arena Model	Manufacturing	Installation	Maintenance
Statistics	Mean, Std, .95CIHW	Mean, Std, .95CIHW	Mean, Std, .95CIHW
Commercial System (X)	13, 0.734, 0.0083	6.13, 1.31, 0.0149	16.5, 5.74, 0.0651
Mega Module System (Y)	14.1, 0.904, 0.0102	3.87, 1.18, 0.0133	15.6, 5.61, 0.0635
Difference between two systems (D = X - Y)	-1.14, 1.16, 0.0132 Means are not equal at .05 level	2.26, 1.76, 0.0199 Means are not equal at .05 level	0.852, 0.686, 0.0077 Means are not equal at .05 level

The results of the DES simulation show that the MegaModule system takes longer to assemble, but is quicker to install and requires less time to maintain. The paired T test verifies that this difference in the measures is statistically significant. The MegaModule therefore meets the desired design purpose, which was to reduce the cost of solar power in the field, by moving a larger part of the expense to the manufacturing process.

6.5 Verification and Validation

System simulation is needed to generate a stochastic model that can be used to analyze costs over the lifecycle. The simulation process requires the data collected in the modeling stage to be prepared for use in the simulation engine. It also requires assumptions and estimations of processes for which there is no data. Setting up the simulation in Arena begins by setting up the process diagrams in Arena, and these are very similar to the SysML diagrams. Input data and simulation parameters can then be tweaked to come as close to reality as possible. Chapter 6 describes in detail the Arena simulation as applied to the MegaModule and typical commercial system. It also discusses the results, which show that the MegaModule has higher labor costs in manufacture but lower labor costs in installation and maintenance. This validates the design intent and intuition of the MegaModule design team.

6.6 Summary

This section presented the simulation component of the framework. The simulation component is shown to consist of three stages. In the first stage data is analyzed and used to approximate distributions for each activity. The results of this analysis are presented. In the second stage, a simulation model is created using the SysML models as a reference. The models for the manufacturing, installation and maintenance stages of the process are shown and described. Finally, the results of this simulation are presented and it is shown that the mega module has a lower lifetime labor cost, even though its manufacturing labor costs are higher.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1. Conclusions

The framework proposed in this paper has been shown to be a good way to evaluate the cost of competing designs over the lifecycle. Each area of inquiry relevant to the research question was investigate and a solution was proposed. The solution was then validated and verified using the case study of the MegaModule and commercial solar power system.

Modularity was presented as an area of inquiry because it provides a holistic method of differentiating between systems. The proposed framework used the method presented by Ji et al.[43] to measure modularity. Using functional and structural similarity a holistic modularity measure can be generated and used for the purposes of differentiation. This method was applied to the MegaModule and commercial system, with the result that the MegaModule was shown to have a higher degree of modularity than the commercial system.

The lifecycle of the solar power systems was presented as needing characterization for the purposes of analysis. This characterization included delineation into stages and activities within these stages. The framework prosed a delineation of the lifecycle into manufacturing, installation and maintenance stages based on the different time durations for activities during these stages. Activities were determined through observation and experience. Further modeling the design in SysML provided a good reference for data collection and communication across stakeholders. Further it supported the level of information required to for the next level of analysis, i.e. the stochastic analysis of costs.

The need for a lifecycle analysis method was presented as the final areas of inquiry relevant to the research question. The need for a viable method exists because of the high variability of activities throughout the lifecycle. Discrete event simulation using ARENA was proposed as the solution those need. The method proposed for discrete event simulation provides a way to utilize collected or projected data to determine labor costs in the three stages, Manufacturing, Installation, and Maintenance. This method was applied to the case study and showed that the MegaModule took more labor time in the manufacturing stage, but saved time in the installation and maintenance stages. Labor time was used instead of cost since cost is proportional to time in general, whereas labor rates can vary.

Finally, the case study demonstrated a situation where a lower degree of modularity led to lower lifecycle labor costs. The method proposed by Guo [49] and Ji et al[43] was an effective way to measure the modularity difference between each system. Further variations in the modularity of each design could be evaluated with the same method to generate a curve to the Frieman curve. This curve would differ in that the x-axis would measure modularity, and the y-axis would measure labor cost. It is expected that the curve would demonstrate a “U” shape, with the low cost modularity sweet spot indicated by the low point of the curve.

7.2. Contributions

The modularity measurement method proposed by Ji et al[43] was a significant contribution to the framework proposed by this paper. This method is critical to determining a holistic factor to differentiate between systems. The LCA methodologies discussed in the literature review section were also important to forming the lifecycle delineations presented in this framework. They can be used as the basis for modifying the framework in the event that the systems being evaluated differ significantly from the ones used to validate this framework.

Data provided by the GTRI team was critical to the evaluation of the input analysis method presented. The process of converting the data into appropriate distributions that can be used by ARENA helped modify the approach. For example, ARENA's own input processing tool was used to generate the distributions. However, use of the MATLAB dfittool provided better options for fitting and more accurate results. As a result this was chosen as the method of input analysis in the final version.

Further the data collection approach presented by Goodman et al [50] helped provide critical insight into the process and challenges of field data collection. Field data collection for solar power installations is wrought with difficulty due to the lack of standardization. The method presented helps capture and categorize the common activities observed over multiple installations. This also proved invaluable to the modeling of the installation process, which essentially strung together these relevant activities into a coherent sequence.

7.3. Limitations

Since the MegaModule is a concept, real world observations cannot currently be obtained. In addition, lifetime data required to validate the results will take 25 years or more to obtain since this is the typical lifespan of a solar power systems. This framework therefore provides an estimated cost performance that could be affected by a variety of factors. Some of these factors include the changes in activities and their labor cost due to automation or changes in the labor supply. For example, automation may make labor cost negligible in the manufacturing, installation or maintenance stages. This would reduce the cost advantage of the MegaModule over traditional systems. An increase in installation labor because of low availability of skilled labor could significantly increase the cost advantage of the MegaModule.

Market dynamics such as these are analogous to environmental effects in finite element simulation of structural systems. In the same way that Finite Element Analysis

(FEA) provides a directional estimate of real world performance, this framework seeks to provide a rough validation of design intent. Like FEA, better data, more data, and more representative virtual construction can improve the accuracy of the results.

7.4. Future work

Discrete event programs have tremendous simulation capabilities that were not taken advantage of in this framework. For example, these programs can be used to determine the utilization of resources and assets, as well as determine bottle necks and areas of process improvement. Future work with this framework could include process improvement and utilization analysis to improve the return on investment (ROI) for the processes used to manufacture, install and maintain the product. Such analysis would further increase the accuracy of the framework in estimating real world cost performance of the system. At the same time it would support an analysis of the feasibility of the new design within existing manufacturing, installation, or maintenance infrastructures.

The scope of the framework could be expanded to include other renewable energy systems. Wind power faces similar challenges that solar power faces and this method could provide a viable means to evaluate competing wind power designs. Further, this framework could also be used to evaluate existing fossil fuel based energy technologies over their lifecycle. In doing so it could provide a baseline cost comparison to evaluate renewable technologies against. In addition to this, the framework could be expanded to include the environmental effects such as carbon emissions, raw material sourcing, or waste cleanup to provide a more holistic comparison methodology.

Finally this analysis could be improved considerably with data gathered over the lifetime of a solar power system. Additional data will help improve the models and activity durations. Expanding the models with resources and other manufacturing parameters will also help improve the overall simulation accuracy. Further, a database of activities and their distributions could be created and published on the internet. This could be a central resource for such simulations and provide designers with a benchmarked and standardized list of activities and parameters. As a results designers can design better systems with their lifecycle in mind and without reinventing the wheel.

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