AN ACTIVITY BASED METHOD FOR SUSTAINABLE MANUFACTURING MODELING AND ASSESSMENTS IN SYSML

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Yuriy A. Romaniw

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AN ACTIVITY BASED METHOD FOR SUSTAINABLE MANUFACTURING MODELING AND ASSESSMENTS IN SYSML

Approved by:

Dr. Bert Bras, Advisor
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Chris Paredis
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Leon McGinnis
School of Industrial Systems Engineering
Georgia Institute of Technology

Date Approved: June 17, 2010

[To all those that helped]

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List of Variables

A	area
a	arbitrary variable
b	arbitrary variable
C	hot strain hardening coefficient, cost
c	arbitrary variable, specific heat
D	diameter, bolt head diameter
d	arbitrary variable, sheet metal bending stroke, bolt unthreaded diameter
E	modulus of elasticity (Young's modulus)
e	arbitrary variable
F	force
f	arbitrary variable
g	arbitrary variable
H_f	heat of fusion
h	arbitrary variable, height
i	arbitrary variable
K	cold strain hardening coefficient
k	spring constant
L	sheet metal bent edge length, extrusion length, sheared edge length
l	fastener length, roller contact length
m	mass, hot strain hardening coefficient
n	cold strain hardening exponent
R	radius
T	temperature
t	sheet metal thickness, material thickness, time
UTS	ultimate tensile stress
v	velocity
W	bending die opening width
θ	angle
ω	angular velocity

Subscripts

1	first indexed element
2	second indexed element
3	third indexed element
avg	average
b	bolt, initial (for rolling)
d	bolt unthreaded diameter
i	initial
f	final
t	bolt major diameter tensile

Summary

Traditionally, environmental impacts of man made products have been determined by performing a life cycle assessment (LCA) on the product. As the name implies, LCA is usually covers the entire life of the product in a so-called “cradle-to-grave” assessment. In determining environmental impacts over the whole product life, LCA’s are reasonably adequate. However, in providing detailed impacts on a particular phase of life, LCA’s are lacking. Detailed assessments are important because very few stakeholders have influence over a product during all phases of life. Stakeholders need detailed impact assessments in their particular phase of life. More detailed assessments give stakeholders more information that can be used for better environmental management (EM) and more environmentally benign operations. In many LCA’s, the manufacturing phase of life has been over-generalized and over-simplified because of its relatively small environmental impact, as compared to other phases of life. Nevertheless, certain stakeholders, such as manufacturing companies, need detailed impact information for the manufacturing phase of life so that they can create a more sustainable manufacturing process. Most traditional LCA’s use a case-based approach, which was deemed to be inadequate. For these LCA’s, the information provided for each case is often quite detailed and specific. However, this makes the assessment less flexible, limiting the quality of the assessment to the degree that the current scenario matches the existing cases. In order to make a more user-specific assessment, a model-based approach was used. To give the model flexibility, a parametric model was created based on mathematical equations that represent various parts of the manufacturing process. To give the model structure, an activity-based costing (ABC) approach was used. Using the ABC structure, the manufacturing process was broken down into activities, each of which was characterized by mathematical models. Large models would be difficult to construct and simulate by hand, so a model was built with the aid of a computer. The modeling language SysML (Systems Modeling Language) was used to create an object-oriented model of the manufacturing process, using the ABC structure. SysML defines overall properties and behaviors of the various elements in the model, while the plug-in tool ParaMagic was used to execute the model via a Mathematica Solver. The model computes carbon dioxide emissions, energy consumption, and waste mass generation for a particular manufacturing scenario. The goal of the model was to quantify environmental impact factors in order to aid manufacturing stakeholders in EM. The overall goal of the research was to determine whether an activity-based, object-oriented model was a valid approach, and whether the computer-aided tools adequately implemented this approach. Findings show that SysML is capable of modeling large and complex systems. However, due to some limitations of ParaMagic, only some of SysML's capabilities were utilized. Nevertheless, ParaMagic is capable of extracting information out of a manufacturing model built in SysML, and solving parametric relations in Mathematica in a timely manner. Timely solutions of complex models are critical for stakeholders keeping a competitive edge.

1 Introduction

1.1 Motivation for Work

Manufacturing companies are becoming more interested in determining what the environmental impact of their manufacturing process. Limiting the environmental impact of a manufacturing process has many benefits to the environment, as discussed in the following section, and to the company, as discussed in Chapter 2, Section 2.2. To determine what the environmental impact is of any manufacturing process, an assessment tool is needed. There is a general lack of adequate assessment tools for the manufacturing process, as discussed in Chapter 2, Section 2.2, so there is a need for a new means of performing assessments on the manufacturing process. Current methods, discussed in Chapter 2, Section 2.2, are structurally sound, but do not take advantage of modern advances in computers and computing technology. Existing methods of performing assessments on manufacturing processes need to be updated to enhance flexibility, traceability of results, and scalability.

This thesis looks at a traditional method of performing an assessment and determines whether current computer modeling capabilities can adequately represent the system according to these traditional methods. Essentially, this thesis tests the capabilities of modern computer modeling languages with respect to modeling a manufacturing system and simulating results for that system.

Chapter 1 of this thesis gives a general introduction to this thesis. Chapter 2 follows with a literature review of work done relating to various topics of relevance to this thesis. Chapter 3 discusses how a traditional approach to performing assessments on manufacturing processes can be modified so that it can be modeled in a computer aided modeling language. Chapter 4 discusses the actual, executable model created in a modeling language of choice. This model is capable of representing some basic manufacturing processes. Chapter 5 demonstrates how the model would be used in a hypothetical situation where a designer wishes to determine an optimal design based on environmental burdens produced by two alternative processes. This thesis concludes with findings and conclusions in Chapter 6.

1.2 Environmentally Conscious Practices

During his presidency from 1901-1909, President Theodore Roosevelt brought about a wave of reform with respect to environmental conservation. He was responsible for establishing five national parks, fifty one bird reserves, four game preserves, and 150 national forests, effectively putting 230 million acres of land under direct United States Government protection (Maier, Smith, & Keyssar, 2006)(Wikipedia, 2010). In 1908, President Roosevelt declared “conservation as a national duty,” during Conference of Governors (Maier, Smith, & Keyssar, 2006)(Wikipedia, 2010). President Roosevelt made it clear that the nation needed to conserve because natural resources were in danger. What was not clear was *why* natural resources were in danger. Though President Roosevelt, and others understood that it was the actions of the society that were harming nature, the exact causes were vaguely understood. It was known that deforestation, overconsumption of water, and over hunting all impacted the environment negatively, but the solution was simply *conservation*. Conservation meant that the society should cut down fewer trees, hunt less often, and consume less water. President Roosevelt’s national parks, forests, and reserves essentially forced society to consume less by making large areas off limits

(Maier, Smith, & Keyssar, 2006)(Wikipedia, 2010). Though this was a major accomplishment, it did little to change the behavior of society and really shown them *why* conservation was important and *why* society needed to change its practices.

In 1962, the book Silent Spring really hammered home *why* society needed to take into account the environment (Carson, 1962). In her book, Rachel Carson indicated that the use of pesticides was harming other plants, animals, birds, and even humans. Where President Roosevelt made it clear that we need to consume less to ensure a proper supply of resources, Carson showed that our actions have much deeper and further reaching effects on the environment than simple overconsumption of resources. Our course of action was not sustainable.

Sustainability can have many definitions, but can be summed up simply as, "the ability to endure." (Wikipedia, 2010) When it comes to human activities, or the activities of a society, *sustainability* can imply the society's ability to continue a certain course of action or maintain certain practices. Since society is dependent on the environment for resources and energy to undertake these actions or practices, society must limit its negative impact on the environment. This would ensure the safety of the supply of resources and energy so that society can sustain its practices. However, current practices may not be sustainable.

There are four questions that need to be asked when it comes to environmentally conscious manufacturing (Emblemsvag & Bras, 2001):

1. What is our environmental impact?
2. Where does it occur (the most)?
3. What should we do about it?
4. What is it going to cost us?

Before we can decide what should be done and how much it would cost, we need to first asses *what* our impact is and *where* is that impact occurring. This leads to the primary focus of the thesis. This thesis assesses whether improvements in modern technology, specifically computing power and capabilities, can help provide a detailed assessment of *what* our environmental impact is and *where* it is occurring. Though *what* and *where* has already been the subject of much research, the use of computers and computer aided tools can bring detail, flexibility, and scalability not yet seen with previous work. This thesis helps in the assessment of impacts by quantifying certain factors that are known to impact the environment negatively while providing a way of seeing exactly where these factors are occurring or being produced.

1.3 System of Interest

The system of interest in this thesis is a manufacturing system. This thesis looks at the production of manufactured products as they go through a manufacturing process. During the manufacturing process, manufacturing operations consume resources and produce or emit waste. Specifically, the manufacturing process consumes fuel (energy) and material resources and produces emissions and waste. Embodied costs of acquiring resources are also included to help give perspective and help distinguish between physically similar resources.

Manufacturing has often been shown to have a relatively small impact on the environment when compared to other phases of the product's life. This can be evidenced by analysis performed on a car engine. It was determined that a typical engine consumes 11.6 GJ of energy during manufacturing and production, while that same engine would consume enough fuel to produce 850 GJ of energy (Smith & Keoleian, 2004).

Manufacturing consumes only 1.4% of the energy as the use phase of the engine. When embodied costs for materials of that engine and end of life disposal or recycling costs are included, the relative impacts of the manufacturing phase become even smaller. However, this may not be true for all products. Therefore, it is necessary to have detailed information about the manufacturing process *before* it is determined that manufacturing has a small impact.

1.4 General Approach

This thesis improves on previous research by taking advantage of the capabilities of modern computers and computer software. Computers allow for increased flexibility, so a model based approach rather than a case based approach can be used. Models are, in general, and improvement over document-based approaches, which would be the case with case based studies or scenario specific assessments. Document based approaches are generally less complete, more difficult to use in analysis, and can be less consistent. On the other hand, model based approaches improve all of this, while adding traceability and flexibility (Fiedenthal, Moore, & Steiner, 2008).

Models are good for, “predicting outcomes and behavior in settings where empirical observations may not be available.” (National Associated Press, 2007) However, this causes models to have a level of uncertainty inherent to them when compared to case based assessments performed using empirical observations. A model can be considered valid if the model, “reflects the behavior of the real world.” (US Department of Energy, 2010) It is impossible to verify a model this way because systems, especially those dealing with the environment, are too complex (Oreskes, Shrader-Frechette, & Belitz, 1994). Nevertheless, a model can still be considered an acceptable representation of the system in its analysis is relatively close to the empirical results, or if it generally represents the major components of the system.

The model built in this thesis is an Activity-Based Costing (ABC) model. A manufacturing process is broken down into activities or manufacturing operations that consume resources. Costs represent environmental releases or other quantities such as emissions, waste, or energy. These activities are assigned to objects that represent products or processes containing multiple operations.

The ABC model is implemented using a computer. The ABC model is built with an object oriented modeling language called SysML (Systems Modeling Language). SysML is flexible and adaptable and is capable of creating many different kinds of models, but SysML relies on third party solvers to execute or simulate models. What this thesis strives to determine is whether SysML is capable of building an ABC model in such a way that a third party solver can simulate or execute the model and return results. These results are quantified costs or environmental burdens that are created during the manufacturing process. These costs can be used to determine the impact manufacturing has on the environment.

The name of the model created in this thesis is an Activity-Based Object Oriented Manufacturing Model, or ABOOM Model.

1.5 Research Question and Hypothesis

This thesis focuses on three questions:

1. **Can an activity-based costing model that describes a manufacturing process be created with the object oriented modeling language SysML?**

Hypothesis: SysML, through MagicDraw, is capable of creating an activity-based manufacturing model

2. **Can this model provide meaningful, scenario-based results relating to the environmental burdens experienced by the system?**

   Hypothesis: The model, using third party solvers like ParaMagic, is capable of returning meaningful results

3. **Can this model be built in such a way as to not diminish usability or user friendliness?**

   Hypothesis: SysML's graphic approach to modeling improves user friendliness while the use the off-the-shelf solver ParaMagic improves usability

1.6 Thesis Outline

This contains six chapters in addition, including this introduction. Chapter 2 is a background and literature review section that looks more in depth into the important subjects of this thesis. Chapter 2 also discusses what has already been done with respect to these topics of interest as well as how it relates to this thesis in terms of lessons learned from and holes or shortcomings of previous work. Chapter 2 strives to answer the question of *why* is this work being done.

Chapter 3 describes the methodology and approach used in this thesis. Chapter 3 introduces the concept of an Activity Space. The Activity Space is an organizational structure that is used to help implement the fundamentals of ABC in a computer aided tool. Chapter 3 defines what an Activity Space is, as well as how an Activity Space helps organize ABC fundamentals to that they can be realized in a computer aided tool. The Activity Space structure ensures that the model adheres to ABC fundamentals while utilizing the modeling benefits offered by computer languages, such as flexibility and scalability. Chapter 3 strives to answer the question of *how* is this work being done.

Chapter 4 describes in detail the actual, executable model constructed in MagicDraw SysML. This includes definition of important elements and their properties, definition of element classes that fit into the Activity Space ABC model, and the definition of interrelationships and behaviors between and amongst these elements. Chapter 4 also attempts to validate the model both with an analysis on the mathematical equations used and a laboratory experiment. Chapter 4 strives to answer the questions of *what* was actually done to create the model, and *does* this actual model support any of the hypotheses.

Chapter 5 examines a hypothetical situation where this model can be used. It walks through an example of a wing structure, describing how the structure is broken down into an Activity Space, and how that Activity Space decomposition is reconstructed to the SysML model. Chapter 5 includes actual numerical results and conclusions about two alternatives for the wing structure, helping determine which choice would be optimal with respect to the costs defined in this thesis. Chapter 5 strives to tie Chapters 3 and 4 together with an illustrative example, as well as answer the questions *what* would an actual scenario model look like, *how* is the Activity Space applied, and *what* is the actual appearance of results once the model is executed.

Chapter 6 concludes the thesis by summarizing what was done, what results were gathered, and how this thesis supports the three hypotheses stated in the previous section. Chapter 6 also includes a description of potential future work that can be done with respect to ABC modeling of a manufacturing system using object oriented modeling and SysML.

2 Literature Review

2.1 Chapter Overview

This chapter begins by discussing environmentally conscious manufacturing. In this section, sustainable manufacturing is defined. Next, this chapter discusses Activity-Based Costing as an approach to sustainably manufacturing analysis. This chapter continues with a section discussing object oriented modeling and SysML, the means by which an Activity-Based Costing model is constructed in this thesis. Finally, a section discussing an existing assessment tool (Homer) that can serve as a benchmark or standard of comparison for the model proposed in this thesis.

Each section discusses the background on each topic before discussing current uses and applications of that particular topic. Each section then discusses problems or issues with that subject that this thesis strives to address. Finally, each section concludes with a discussion on how the subject relates to the thesis and how the thesis strives to solve or mitigate the problems highlighted.

2.2 Environmentally Conscious Manufacturing

2.2.1 Description and Background

Manufacturing is one of the four phases of life for a product's life cycle. A product is defined in by the International Organization for Standardization as "any goods [sic] or service." Products are broken into four parts: services, software, hardware, and processed materials. (ISO 14000:2006, 2006) For the purposes of this thesis, primarily hardware and processed materials are considered when a product or a manufactured product is discussed. The Environmental Protection Agency defines a products life cycle as follows (Environmental Protection Agency, 2009).

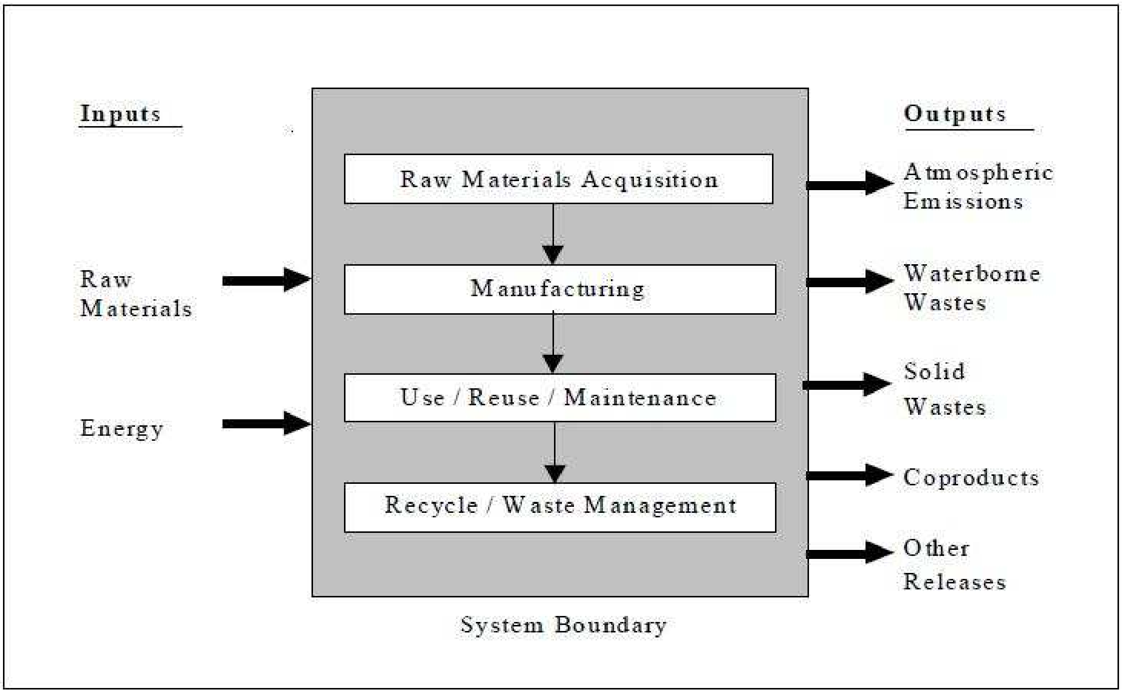

Figure 1: Environmental Protection Agency's definition of a product life cycle

Each phase of life consumes raw materials and energy, while producing a number of outputs. These outputs can have adverse effects and can be extremely harmful to the environment. Atmospheric emissions, such as carbon dioxide, can lead to global warming (Ramaswami, Millford, & Small, 2005). Solid wastes can contain harmful elements, such as lead or arsenic, which can contaminate land and water (Ramaswami, Millford, & Small, 2005). For the reasons discussed in Chapter 1, Section 1.2, we need to be conscious of the outputs of each phase of life so that we do not harm the environment beyond its ability to handle.

This thesis focuses on the manufacturing phase of life, which consumes raw materials and energy and produces the outputs shown in Figure 1. Environmental releases from the manufacturing process can include carbon dioxide, NOX emissions, SOX emissions, volatile organic compounds, solid waste mass, and harmful chemicals (Cattanach, Holdreith, Reinke, & Sibik, 1995). Producing these wastes as well as consuming raw materials and energy puts a burden or cost on the environment. This cost needs to be mitigated.

There is a growing desire for environmentally conscious manufacturing. Sources cite various adverse effects of ignoring the environment during manufacturing, including but not limited to, "global climate change, stratospheric ozone depletion, and loss of the earth's biological diversity." (Kalpakjian & Schmid, 2001) To reflect the concern for the environment, multiple legislative acts have been implemented to try to help ensure the safety of the environment. Several of these acts include the Occupational Safety and Health Act (OSHA), Clean Air Act, Resource Conservation and Recovery Act, and the Comprehensive Environmental Response, Compensation and Liability Act (Cattanach, Holdreith, Reinke, & Sibik, 1995)(Kalpakjian & Schmid, 2001).

Manufacturing must become more sustainable. The International Trade Administration defines sustainable manufacturing for their sustainable manufacturing initiative as follows (International Trade Administration):

> … sustainable manufacturing is defined as the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound.

There is a strong correlation between increasing efficiencies and decreasing waste (Cattanach, Holdreith, Reinke, & Sibik, 1995). This means that apart from regulatory compliance, environmentally conscious manufacturing can lead to cost savings through increased efficiencies. Reducing unnecessary costs through sustainable manufacturing practices can even give a company a competitive advantage in the market (Dills & Stone, 2007).

In order to attain a sustainable manufacturing operation, an assessment needs to be performed to see where a current operation stacks up.

2.2.2 Current Uses and Applications

One approach to determining the environmental burdens of a product is to perform a Life Cycle Assessment (LCA). A standard definition of an LCA can be found with the United States Environmental Protection Agency (EPA). Their definition is as follows (Environmental Protection Agency, 2009):

> [Life Cycle Assessment] is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service by:
>
> - Compiling an inventory of relevant energy and material inputs and environmental releases
> - Evaluating the potential impacts associated with identified inputs and releases
> - Interpreting the results to help [the person performing the assessment] make a more informed decision

The EPA definition briefly defines what an LCA is, but for a more specific definition the International Organization for Standardization published standards act as a basis. The ISO 14000 guidelines for an LCA correspond closely to the definition proposed by the EPA. The general definition of an LCA, according to ISO 14000 is the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle."(ISO 14000:2006, 2006) The ISO 14000 guidelines say than an LCA contains the following four steps (Emblemsvag & Bras, 2001)(ISO 14000:2006, 2006):

- Goal definition and scoping – ISO 14040
- Inventory analysis – ISO 14041
- Impact Assessment – ISO 14042
- Interpretation – ISO 14043

As can be seen in ISO 14040-14043, the ISO guidelines match closely to the EPA definition. When referring to an LCA, the ISO 14000 guidelines are assumed since they provide slightly more detailed descriptions than the general EPA definition. However, the two definitions are effectively interchangeable for the purposes of this thesis.

According to both definitions of LCA, the work done in this thesis can best be defined as a Life Cycle Inventory (LCI). The International Organization for Standardization defines in ISO 14000 that an LCI is the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle." (ISO 14000:2006, 2006) The ISO 14000 definition of an LCI differs from the ISO 14000 definition of an LCA in that an LCA contains an LCI, but goes beyond an LCI to evaluate the environmental impacts of the inputs and outputs for a product. This thesis proposes a model that combines various resource inputs and computes environmental costs and releases, satisfying the definition of an LCI. What the model does not do is assess what the impacts of these environmental costs and releases, nor does the model interpret the results. It is assumed that the general effects and impacts of environmental releases are negative or detrimental to the environment, though detailed impacts are not analyzed. Interpretation of the results is left up to the user of the model. It can be assumed that this thesis is primarily addressing issues with LCI's, and not LCA's as a whole. Nevertheless, since LCI's are a fundamental part of LCA's, many attributes and shortcomings of LCA can be shared (but do not have to be) with LCI.

An approach to performing an LCA is by performing a Life Cycle Impact Assessment (LCIA), which is defined by the International Organization for Standardization as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product." (ISO 14000:2006, 2006) An approach to determining the magnitude and significance of environmental impacts is with an indicator values. An indicator value is a relative numerical representation of the overall impact experienced by a product, process, or operation. Impact assessments that use indicators calculate the indicator based on the potential harm that environmental releases can cause. Indicators can be calculated by assigning a weighted factor to environmental releases, corresponding to their relative severity and adverse effect on the environment. Indicators consolidate information in attempt to understand relative impact. One such LCIA that uses an indicator value is Eco-Indicator 99.

Eco-Indicator 99 bills itself as, "A damage oriented method to Life Cycle Impact Assessments." (Product Ecology Consultants, 2000) Eco-Indicator has a database of resources and processes, each of which us assigned an Eco-Indicator score given in millipoints. The score is an impact assessment value that represents the overall environmental burden realized by that resource or process. The score is calculated with a mathematical algorithm that weighs different values and impacts to give a single number that is representative of the overall resource's or product's impact (an *indicator* value). Lower scores indicate lower environmental impact. For example, 100% recycled aluminum has an Eco-Indicator score of 60 millipoints per kilogram, while 100% virgin aluminum has a score of 780 millipoints per kilogram. It can be seen that recycled aluminum has an impact approximately 13 times smaller than that of virgin aluminum. Processes also have scores associated with them. For instance, machining (e.g.: milling, turning, drilling) has a score of 800 millipoints per cubic decimeter removed. Eco-Indicator's approach of using indicators extends its ability beyond an LCI to an LCIA, but it still suffers from some of the problems discussed in the following section.(Goedkoop & Spriensma, 2001)(Product Ecology Consultants, 2000) Some other major LCI databases and indicator approaches are EcoInvent, SimaPro 7, PE International's GaBi or Ecolbilan's TEAM.

2.2.3 Issues with Current Uses and Applications

The problem with using an LCA to perform an assessment on a manufacturing process is that an LCA is generally too broad in scope. An LCA cannot provide the necessary resolution that is needed to make small changes in the manufacturing process. Furthermore, the use of indicator based assessments further destroys resolution. An LCA and different approaches to LCIA are good for broad analysis, but not good for detailed analysis for manufacturing.

Since this thesis focuses on the LCI part of an LCA, unresolved problems relating to creating an inventory for an LCA are looked at. There are three general problems that plague the inventory phase of LCA. The first issue is the allocation of values, burdens, impacts, attributes, etc. The question of to whom or to what these values belong to is a relatively controversial issue and there is much debate as to where different values are allocated and why. The second issue is that inventories lack cutoff (also known as *negligible contribution*) criteria. Since not all properties and attributes of systems are modeled, it is important to determine how much of the system should be included.

Truncating an inventory based on given cutoff criteria can return incomplete of insufficient information about the system, inhibiting the assessment. Inventories need to make these criteria more clear so that proper use and analysis of the inventory can be utilized. The third issue with LCI's is local or scenario-based uniqueness. Life Cycle Inventories need to be flexible enough to represent differences in various, non-similar scenarios. If the LCI is too inflexible, then the LCA may become over generalized, possible omitting important impact factors or effects of case-specific information. (Reap, Roman, Duncan, & Bras, 2007)

Eco-Indicator 99 does well with flexibility. However, there is no good way for a user to adjust the Eco-Indicator 99 database. This goes back to the unresolved issue of local uniqueness in models. Eco-Indicator 99's fidelity depends on how well a particular scenario matches up with existing inventory and database entries. Flexibility is hindered more due to Eco-Indicator 99's lack of transparency. Eco-Indicator 99 calculates weighted impact values for each of its entries. For a user to modify the database, the user would have to repeat the algorithm used to calculate the Eco-Indicator score. Also, the user must accept the relative weighting of impacts assigned by Eco-Indicator 99. The algorithm and methodology used to calculate an Eco-Indicator score can be found in their methodology manual (Goedkoop & Spriensma, 2001). However, the methodology is complex and clear justification for weighing of factors is not detailed for all parts of the model (assuming some parts of the model and the algorithm are proprietary). Furthermore, the underlying model is not clear to a casual user and has to be researched.

Detailed analyses in the manufacturing field can be found in a number of case studies done my Emblemsvag and Bras (Emblemsvag & Bras, 2001). These case studies use an approach called Activity-Based Costing that gives finer resolution to impacts experienced during the manufacturing process. However, Emblemsvag and Bras experience an issue with local uniqueness. The issue of local uniqueness is that LCA's may not be able to represent a system uniquely enough. Emblemsvag and Bras use a case-based approach that makes their analysis *too* unique.

2.2.4 Thesis Relevance

There are several needs identified in the literature. The first is that an assessment must be able to be performed on a manufacturing process, providing adequate resolution. This resolution is generally not provided by complete LCA's, so a more specific approach is necessary. The approach used must help mitigate the three problems of properly allocating burdens, determining cutoff criteria, and establishing adequate local uniqueness. The issue of local uniqueness is important because it means the model must be flexible. Flexibility means that the model should be able to account for differences between scenarios without becoming too specific and losing cohesive structure.

2.3 Activity Based Costing

2.3.1 Description and Background

Activity-Based Costing (ABC) is a cost accounting method first used in the 1970's and 1980's in the manufacturing sector. Its fundamental principles were studied and formalized by the Consortium for Advanced Management – International (now known simply as CAM-I) (Wikipedia, 2009). What developed was a general cost structure, known as the CAM-I cross shown in Figure 2, which is applicable to many different studies (Billington, 1999)(Cooper, 1996)(Cooper & Kaplan, 1988)(Cooper & Kaplan, 1991)(Cooper & Kaplan, 1998)(Emblemsvag & Bras, 2001).

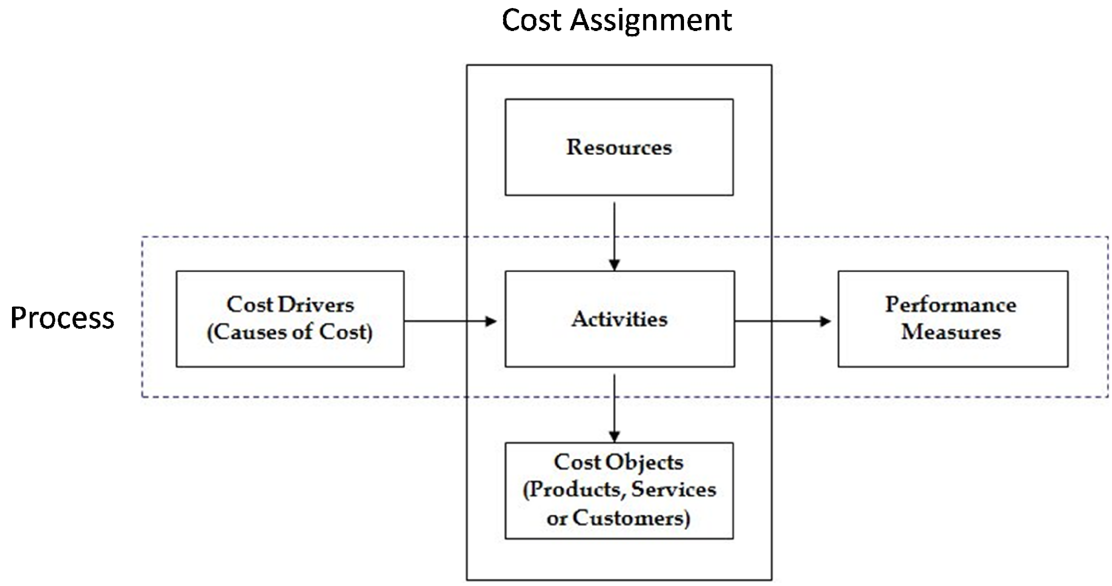

Figure 2: CAM-I Cross, defining fundamental Activity-Based Costing Structure

Activity-Based Costing can be viewed from two perspectives, both centering around the activity. The process perspective says that activities contain cost drivers, which are the causes of costs. These activity costs can be aggregated or otherwise utilized to determine overall performance. The second perspective is the cost assignment perspective. The cost assignment perspective says that activities consume or use resources and are in turn consumed or used by objects. The cost perspective of the CAM-I tree is important to manufacturing since the three elements can represent corresponding elements in manufacturing: manufactured products behave as cost objects, manufacturing operations are activities, and resources represent natural resources consumed by the manufacturing process.

It wasn't until the late 1980's when Robin Cooper and Robert S. Kaplan truly codified a fundamental groundwork for ABC. In a series of articles, Cooper and Kaplan reintroduced the basic concepts formalized by CAM-I, while exhaustively looking at the uses, benefits, functionality, and shortfalls of ABC. Much of the work done with ABC since Cooper and Kaplan's first publication in 1988 derives much of its structure from those articles published. Though there are a few modifications as to the exact way in which Cooper and Kaplan's ABC structure is implemented, the influence is clear (Wikipedia, 2009)(Cooper, 1996)(Cooper & Kaplan, 1988)(Cooper & Kaplan, 1991)(Cooper & Kaplan, 1998).

2.3.2 Current Uses and Applications

In manufacturing, ABC has been applied to a number of systems. Demonstrating an excellent ability to model systems across many levels of resolution, ABC can be applied to unit operations, like a forging operation (Rezaie, Ostadi, & Torabi, 2008), to intermediate systems, such as a shop floor consisting of multiple operations (Barth, Livet, & De Guio, 2008), to systems consisting of multiple manufacturing processes spread out over multiple manufacturing plants (Emblemsvag & Bras, 2001).

With respect to large scale systems, Emblemsvag and Bras looked at a number of case studies that include a toy manufacturer, a shipping company, a floor carpeting manufacturer, and a mattress manufacturer (Emblemsvag & Bras, 2001). In the case of the carpet manufacturer, the system was spread over four manufacturing plants. Emblemsvag and Bras organized the system by manufacturing plant by creating activities such as "Produce at R.C.A. Plant." This activity contained other activities, which in turn contained even more atomic activities. This created an activity hierarchy where higher level activities could be defined as a set of lower level activities. The hierarchy in this thesis is similar to the hierarchy done by Emblemsvag and Bras, but rather than creating a hierarchy of activities, this thesis creates a hierarchy of objects. In other words, "Produce at R.C.A. Plant" would be represented by an object, such as "R.C.A. Plant," which would contain processes, treated as objects themselves, with would contain unit activities. Emblemsvag and Bras assess costs using what they call a "waste index." (Emblemsvag & Bras, 2001) The waste index is an indicator value that is calculated based on a mathematical algorithm and is used to assess the relative environmental impact experienced by a manufacturing process.

2.3.3 Issues with Current Uses and Applications of Activity-Based Costing

The primary issue with current applications of ABC is that most of the applications are case-based. The fundamentals of ABC presented by Cooper and Kaplan are present in many of the examples of how ABC can be applied, but each application is fundamentally unique to that particular case. This limits flexibility and reusability of some of the work that has already been done with respect to ABC.

This does not mean that there have not been model based approaches. There exist many computer tools and software that can implement an ABC model to a variety of systems. However, the issue with these is that they are financial costing models, not environmental costing models. Activity-based assessment tools generally ignore environmentally conscious metrics. With respect to sustainability, ABC tools look at financial sustainability and not environmental sustainability. This makes them less useful for trying to establish an environmentally sustainable manufacturing process.

2.3.4 Thesis Relevance

There is a general lack of model based ABC that takes into account environmental metrics. Activity-based models, computer based or otherwise, do not account for environmental burdens. Assessments that do use an ABC structure and account for environmental burdens are case-based, and not model based. A model based approach is preferable because of reusability, flexibility, and general adaptability to different situations. This thesis proposes a model based ABC approach that accounts for environmental burdens. Taken in parts, model based ABC with environmental metrics has already been addressed in the research. What has not been done is that these three parts have not been combined into a single assessment method or tool. This thesis attempts to merge model based ABC with environmental metrics on a computer based platform.

2.4 Object Oriented Modeling and SysML

2.4.1 Description and Background

Object oriented modeling has its origins in computer programming. Prior to object oriented modeling, computer programs were "procedure based," where functions were grouped together to form a single unit. Object oriented modeling improved on this concept by treating the problem as a set or interrelated and interdependent objects, rather than sets of functions. Object oriented modeling was quickly expanded to systems level engineering, where a system would be decomposed into stand-alone objects that could b used and reused independently (Fiedenthal, Moore, & Steiner, 2008). This was seen as a general improvement in the modeling of broader system because object oriented modeling does not only, "effectively support the establishment of large and complex systems by decomposing the problem into its natural entities… it can also model the interrelationships between [these entities].” (Xu, Chen, & Xie, 2006)

SysML is a modeling language released by the Object Management Group for the purpose of being, “a general-purpose graphical modeling language.” (Object Management Group) It is currently being used as a plug-in for the program MagicDraw UML. SysML is an object oriented language that is based on Unified Modeling Language (UML) Unified Modeling Language primarily focuses on software engineering systems, while SysML expands on UML to include a variety of systems. There are several key differences between UML and SysML, as can be shown graphically with the following chart (Object Management Group).

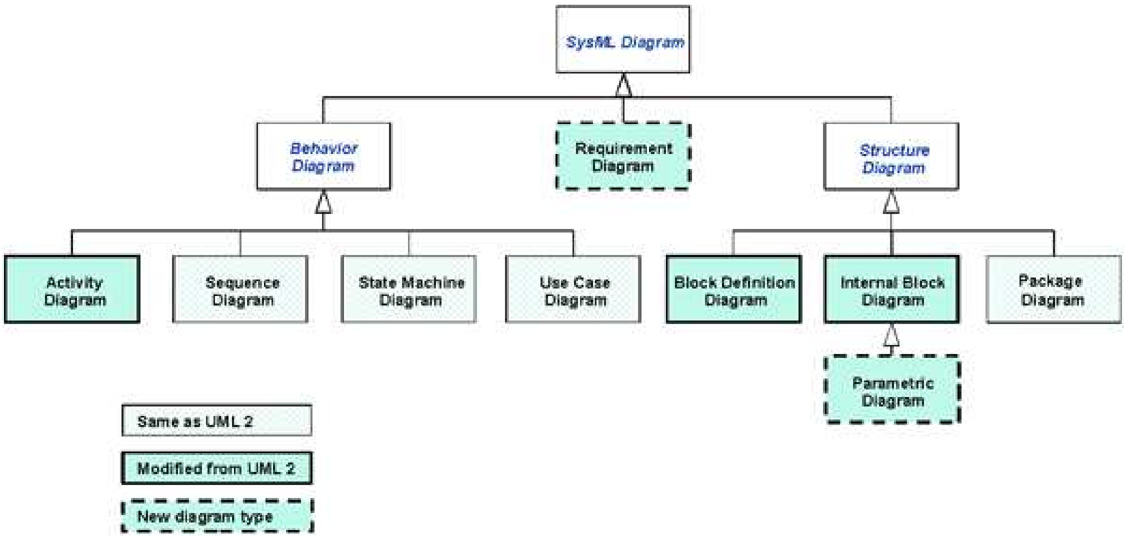

Figure 3: Chart showing SysML diagrams, comparing differences with UML

SysML is generally considered and improvement over UML (Balmelli, 2007)(Colombo, Del Bianco, Lavazza, & Coen-Porisini, 2007). Two key aspects that SysML has that make it superior to UML is that SysML introduces requirements diagrams and parametric diagrams. Requirement diagrams aid in requirement matching and requirement traceability. Secondly, and more important to this thesis, SysML parametric diagrams aid in the definition of mathematical equations and parameter traceability. Parametric diagrams essentially allow a modeler to clearly define the mathematical behavior of a system. This is critical to this thesis, since parametric diagrams are used to define the mathematical relationships that are later accessed by a third party solver to execute and simulate the model.

MagicDraw SysML stores its file in an XML file format. This make is relatively easy to access and extract information from SysML model files. This important feature allows for the construction of plug-ins that can extract information from, simulate, or execute the model. These plug-ins usually parse through a MagicDraw SysML file looking for important information. Next, plug-ins translate or wrap this information in such a way that a third party solver or simulator can understand it. Finally, plug-ins send the translated information to the solver where it is executed. Some plug-ins go one step further and extract information from the solver, translate it, and send it back to MagicDrqw where the SysML model is updated. Since SysML is only a language, and MagicDraw SysML has no inherent or built in simulation or solving capabilities, the ability to easily use third party solvers is very important.

2.4.2 Current Uses and Applications

SysML has a variety of uses and applications. A variety of diagrams allows many different kinds of systems to be described, while still allowing each system to be described many different ways. Several systems that are described using SysML are a hydraulic backhoe (Johnson, Jobe, Paredis, & Burkhart, 2007)(Johnson, 2008), a rain sensing windshield (Balmelli, 2007), flap linkage assembly (Peak, Burkhart, Friedenthal, Wilson, Bajaj, & Kim, 2007), factory work flow (Huang, Ramamurthy, & McGinnis, 2007), and a camera based surveillance system (Fiedenthal, Moore, & Steiner, 2008). The SysML plug-in for MagicDraw comes with several other systems defined, such as an unmanned aerial vehicle, a satellite, and a financial costing model. As seen in these examples, SysML can be used to describe a large variety of systems.

Some applications of computerized veriosn of SysML also use a solver. For instance, the hydraulic backhoe model uses Modelica to execute the system (Johnson, Jobe, Paredis, & Burkhart, 2007)(Johnson, 2008), while the factory floor model uses Em-Plant (Huang, Ramamurthy, & McGinnis, 2007). Some models simulate activity diagrams using Petri-Net simulation tools like NetDraw, TINA, or SELT (Linhares, deOliveira, Farines, & Vernadat, 2007), while others simulate activity diagrams using Descrete-Time Markov Chain (DTMC) solvers (Jarraya, Soeanu, Debbabi, & Hassaine). Translation of SysML models to Matlab, Simulink, and Excel has also been demonstrated (Kalianasundaram, 2010)(Azevedo, 2010)(InterCAX, 2009)(Qamar & During, 2009). The solver used in this thesis is Mathematica, which is accessed by a plug-in called ParaMagic developed by the company InterCAX. ParaMagic is capable of using both Mathematica and OpenModelica as a solver, but it also demonstrates the ability to send information to Matlab and Excel (InterCAX, 2009).

2.4.3 Issues with Current Uses and Applications

The primary issue with MagicDraw SysML is that it does not have a built in solver of any kind. This means that some models expressed in SysML are solely descriptive models. Though this can be extremely useful in data storage and information traceability, it is undesirable if the model needs to me simulated or executed. To do this, plug-ins must be made to translate what is in a SysML model so that it can be understood by a third party solver. This has its own set of issues.

The first issues is that most plug-ins are custom built by researchers who wish to execute or simulate their models a specific way. This diminishes the usability of SysML if users must create their own plug in to solve the model they need solved. Some ready built, commercial solvers do exist. One example is ParaMagic, which is fully functional and can be purchased as a plug-in for MagicDraw UML along with SysML. Even though some plug-ins can come ready to use, there is a second issue that comes up.

The second issue is a conflict between plug-ins and SysML itself. Plug-ins usually need a strict model structure in SysML in order to properly parse the XML file and extract the correct data. For instance, the DTMC plug-ins require that an activity diagram be structured a certain way. Furthermore, plug-ins like ParaMagic only utilize two types of SysML diagrams: parametric diagrams and block definition diagrams, which in turn have to be properly structured. Plug-ins need a strict modeling structure, while SysML tries to be as flexible as possible, causing a conflict of interest.

The resolution of these two issues can be found in first choosing an off-the-shelf solver that does basically what the user wants so that the modeler does not have to build a custom solver, and next using and implementing a model structure that fits into the framework required by the solver. However, this can lead to complications for this thesis.

2.4.4 Thesis Relevance

This thesis chooses an off-the-shelf solver. This solver is ParaMagic. Choosing ParaMagic improves the usability of the model created in this thesis. However, ParaMagic requires anything that is to be solved needs to be found in a block definition diagram or a parametric diagram. Additional diagrams are purely descriptive. This has great implications for this thesis. ParaMagic would be the plug-in used to return meaningful results, while at the same time improving usability by not requiring a user to custom build a solver. This supports the second and third hypotheses. However, limiting SysML to only block definition diagrams and parametric diagrams may make it difficult (or impossible) to build the ABC model that is desired. The *activity*-based costing model would logically be built using *activity* diagrams, but ParaMagic would not be able to use these diagrams. An off the shelf plug-in that can solve activity diagrams can be selected, but no known commercial solver exists. There is second problem with using activity diagrams, which is that activities in SysML do not store values or express multi-scale, part-to-whole containment well. This means that the hierarchical structure of ABC could not be expressed and costs could not be assigned properly. The first hypothesis is in jeopardy of being shown to be false.

2.5 Assessment Tools

2.5.1 Description and Background

There are a variety of tools available to perform an assessment on a situation. These tools vary greatly in appearance and structure. The overall purpose of an assessment tool is to help perform an assessment by standardizing some inputs and outputs.

2.5.2 Current Uses and Approaches

The simplest tools are basically computerized back-of-the-envelope calculations, while more advanced tools provide more significant feedback. An example of a very rudimentary assessment tool is a cost estimator on the Home Depot website. The cost estimator compares lifetime monetary and carbon dioxide savings of switching from incandescent light bulbs to compact fluorescent light bulbs (CFL's). The assessment tool allows the user to input bulb wattage and number of bulbs to be replaced. The tool then uses basic mathematical models to calculate the amount of money and carbon dioxide saved during the life of the new bulb. (Home Depot, 2010)

An example of a considerably more advanced impact assessment tool (though not strictly an LCA) is the National Renewable Energy Lab's tool Homer. (National Renewable Energy Lab, 1993) Homer assesses a variety of costs, including money and carbon dioxide emissions, associated with meeting an electrical load by different means. Homer has a user specify a load then has the user specify how that load is to be met. The load can be met with grid electricity, generators, batteries, and alternate power generation systems. Homer uses complicated underlying mathematical models to calculate the emissions, energy requirements, peak load times, peak power production times, cost per unit energy, etc. Homer's costs are given per unit time, but take into account finite life of elements included in the model. Homer requires a large amount of user input, but provides a large amount of feedback. (National Renewable Energy Lab, 1993)

These assessment tools, whether they are an LCA, LCI, or general impact assessment tools, need to be measured up against the three requirements for a computer-based model: usability, transparency, and flexibility.

2.5.3 Issues with Current Uses and Applications

Current assessment tools can have two problems: they are not transparent and they cannot be modified adequately. Tools like Homer allow a user to add new elements and perform new assessments, but there is a lot of behind-the-scenes activity that is going on in the tool that is not made clear to the user. A user defines inputs and hits a solve button, Homer solves and then spits back results. The user cannot trace back results to their sources adequately, nor can a user determine *why* a result is what it is. Though tools like Home do allow the user a great deal of flexibility when it comes to adding new elements, the fundamental structure of Homer cannot be changed. This may be a good thing in some cases, but a bad thing in cases where the scenario being modeled has specific unique features that are not expressed by Homer. Tools need to be transparent to enhance traceability and the tools need to be adaptable so that they can account for the different demands of different scenarios.

2.5.4 Thesis Relevance

Overall, Homer is a good tool. It can serve as a solid baseline for comparison for the model developed in this thesis. The third question about usability of the ABOOM Model is answered with a comparison to Homer. Specifically, speed of constructing a model, solve time, and results are compared between Homer and the ABOOM Model.

2.6 Conclusions from Literature Review

Based on the readings, it is clear that there are holes in existing research. Firstly, existing major assessment practices do not provide the degree of resolution required to gain meaningful understanding of environmental burdens produced during a manufacturing process. Secondly, alternate approaches that do give adequate resolution are done on a case-by-case basis. Furthermore, these approaches do not take advantage of advances in computers and computer aided technology. This leads to inflexibility, lack of results traceability, and difficulties when it comes to scalability. However, when it comes to computer aided technology, there is a general lack of standardization. Each computer aided model is constructed using unique modeling practices and uses custom built solvers to run a model simulation.

The work done in this thesis addresses the first issue by taking a tried and true method of performing detailed assessments and applies it to the manufacturing process. This thesis addresses the second issue mentioned by creating a computer aided model of the manufacturing system, using the traditional approach. Lastly, this thesis addresses issues with standardization by applying a common modeling structure using a flexible, off-the-shelf modeling language that uses a generic, off-the-shelf solver.

3 Methodology: An Activity-Based Costing Approach

3.1 Chapter Overview

This chapter discusses the approach used to create the ABOOM Model. This chapter begins by defining the scope and system boundary of the ABOOM Model. Then the chapter discusses the underlying fundamental principle behind the model in Section 3.4 where the concept of an Activity Space is introduced. Section 3.4 justifies the use of an activity-based approach, then discusses how a manufactured product can be decomposed such that it fits into an ABC structure, and the section finishes with defining what an Activity Space is and how it is helpful and beneficial in organizing the system. The organization provided by an Activity Space helps bridge the gap between principles of ABC and computer-aided, object oriented modeling. The object oriented language of choice, as well as the way in which the Activity Space is modeled in the language is discussed in Section 3.5. The chapter then goes on to describe data gathering and methods of model validation in Section 3.6. Section 3.7 introduces the broad concept of a federated model. Though detailing a federated model is considered outside of the scope of this thesis, the section indicates what elements could be considered while creating a federated model for the system of interest. The chapter finishes with a general discussion on the approach used as well as how the approach and the concepts introduced in the chapter help answer the three research questions defined in Chapter 1, Section 1.7. In particular, this chapter looks at how a manufacturing model can be defined such that it can be realized with an object oriented language (first research question).

3.2 System Definition and Scope

As mentioned earlier, the system of interest is a manufacturing process. The model is not designed to be an entire LCA itself, but the tool represents a portion of an LCA. The EPA defines a system boundary for their definition of an LCA with the following figure(Environmental Protection Agency, 2009).

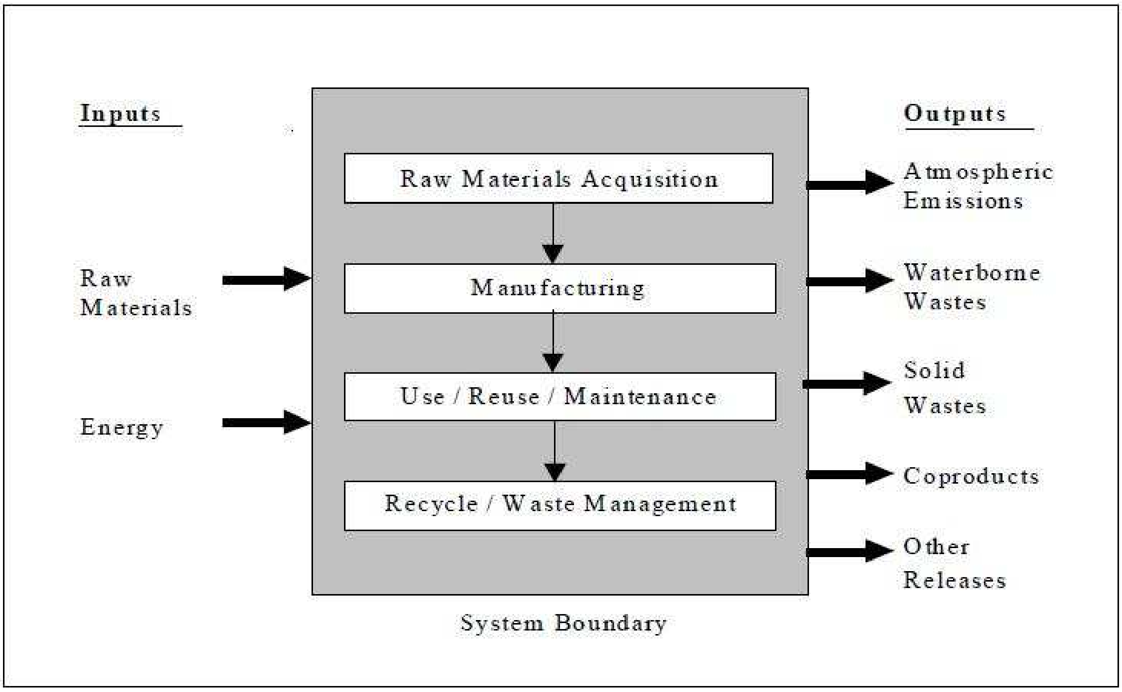

Figure 4: The Environmental Protection Agency's life cycle assessment system boundary

This thesis focuses primarily on the box labeled *Manufacturing*. Mathematical models are used describe what goes on inside this box. In order to provide some context to the manufacturing phase of life, the model developed allows for information about *Raw Material Acquisition* to be seen, but this information is not modeled mathematically and is assumed to be an input derived from databases. The specific equations that represent the *Raw Material Acquisition* box are not modeled, but information about this phase of life is present. The rest of the product's life cycle, represented by the boxes labeled *Use/Reuse/Maintenance* and *Recycle/Waste Management* are considered beyond the scope of this thesis.

The ABOOM Model developed in this thesis accounts for both raw material inputs and energy inputs. Raw material inputs take the form of metals, lubricants and coolants, and some other raw materials. Not all of the outputs listed in Figure 4 are included in the model. Under *Atmospheric Emissions*, carbon dioxide produced during the process is included. Any material waste produced during manufacturing is assumed to fall under *Solid Wastes*. This is assumed even for liquid wastes because during manufacturing, liquid wastes like lubricants and coolants can get mixed in with solid waste. The result is a slurry mix that is normally quantified as a mass amount assumed to be mostly solid.

It is assumed that carbon dioxide is released by consuming fuel to provide energy for a process. In the case of some energy providing resources, such as electricity, the emissions are generated far away from the manufacturing plant. These emissions are included in the model and are considered within the system boundary. Energy emissions associated with acquiring energy providing resources is assumed to fall under *Raw Material Acquisition*.

3.3 Methodology Overview

As mentioned, the system is a manufacturing system. The system is decomposed so that it fits into an activity-based structure. This structure is used as the framework for an object oriented model, built with SysML. Mathematical models are the backbone of the ABC model and are represented in SysML parametrically. These mathematical models are used to quantify costs.

The costs are broken into two types. The first is the manufacturing costs. These are the costs associated directly with the manufacturing process. Examples include energy costs for operating a machine, emissions produced while consuming fuel to perform an operation, and waste mass produced machining a feature into a part. Manufacturing costs assume that the inputs are harvested ideally. To represent the cost of harvesting materials, the second type of cost used is embodied costs. Embodied costs are defined as the cost accrued "to produce, process, and transport the resource to where it is actually needed." (Emblemsvag & Bras, 2001) These costs are representative of costs accrued during raw material acquisition. The resources are "needed" in the manufacturing phase, so embodied costs represent costs prior to manufacturing. Examples are emissions and energy costs associated with harvesting a material, refining it, getting it into a ready-to-consume form, and transporting it to the manufacturing plant. Since embodied costs are assumed to be derived from databases and are not explicitly calculated, they may be incomplete in terms of representing *everything* occurring prior to manufacturing. The purpose of including embodied costs in a manufacturing model are to give a *more* complete picture, with the understanding that the model may not be *absolutely* complete. To reiterate, manufacturing costs reflect the costs in the *Manufacturing* box of Figure 4, while embodied costs represent the costs in the *Raw Material Acquisition* box.

The system is based around what is called an Activity Space. The Activity Space is created by defining all of the manufacturing operations or activities required to make a product. This list of activities is then organized and grouped in specific ways that would allow analysis to be performed. The Activity Space concept and approach is described in detail in the following sections.

3.4 Activity-Based Approach

3.4.1 Justification of an Activity-Based Approach

Two major assumptions are needed in order to allow an activity-based approach to be used. The first assumption is that a product can (to a reasonable extent) be defined as a set of discrete operations or activities. The second assumption is that the activity costs are consistent and predictable. Though the literature has shown that ABC can be applied to manufacturing systems, it is important to independently justify that such an approach can be used for a system more similar to the one described in this model. To do this, an experiment by Prashant Lodhia and Rebekah Drake of Wichita State University is analyzed.

Lodhia and Drake designed a simple part that was to be machined in a computer numerical control (CNC) machine. The data gathered consists of the machine's power consumption as a function of time as it performed its various functions. The part manufactured is shown in Figure 5.

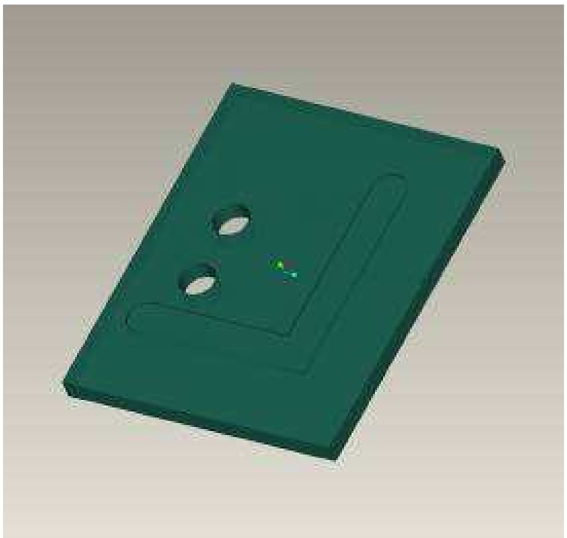

Figure 5: Sample part machined

The part consists of an L-shaped channel and two drilled holes. The machine went through a number of stages, including start up, warm up, machining, and bit changes. The purpose of the work was to reduce what Lodhia and Drake call “Muda,” which they define as waste. Waste includes not only material waste, but also wasted time and energy. Their work focused on the energy consumption of a machine during machining in order to identify *what* is energy being used for and *where or when* in the process is this energy being consumed. This information could be used to help improve the process. The power consumption as a function of time can be seen in Figure 6. (Lodhia & Drake, 2008)

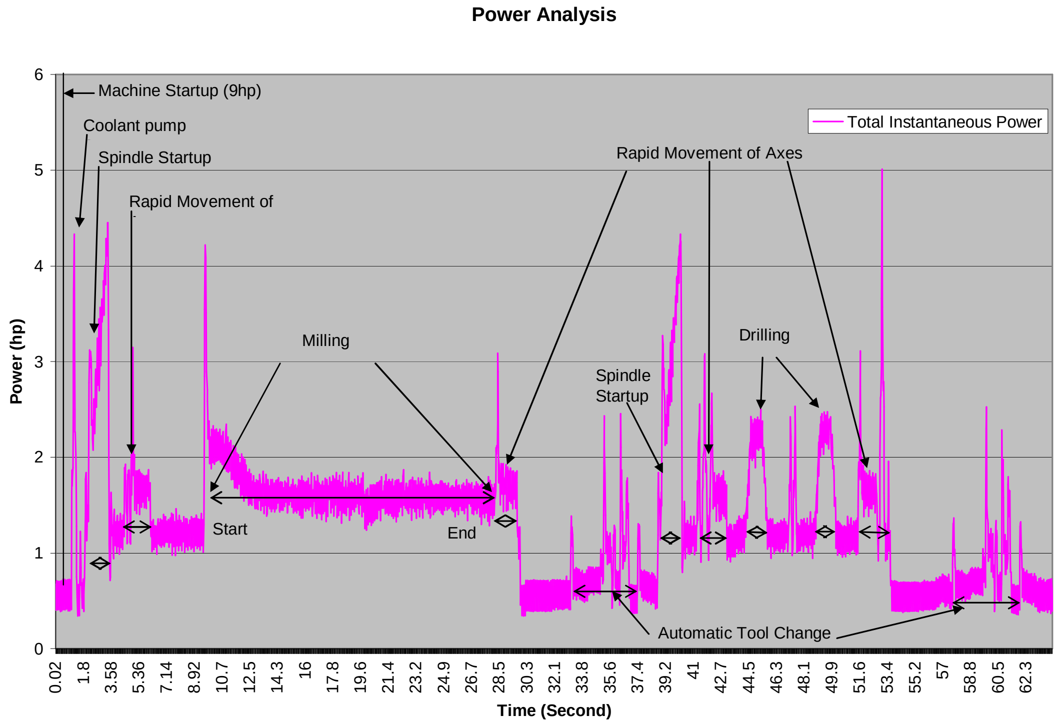

Figure 6: Power vs. time plot for machining a part

In the plot, several important things can be seen. The first is that discrete actions and activities can indeed be identified. These actions are labeled in the plot. This leads to the conclusion that a manufacturing process can be divided up into a set of discrete activities that describe a manufactured part. The second piece of information that is evident is that repeating actions are consistent and predictable. One example can be seen in the rapid movement of axis as the machine's tool bit repositions itself. The second example is the drilling operations, each of which is seen as a slightly domed peak. The energy consumed during an operation is the integral of the power consumed curve over a time interval. It can be seen that the duration of the peak for each drilling operation is similar, therefore so are the magnitudes of energy consumption. This means that the energy consumed is not only consistent between operations, but also predictable.

For this thesis, a similar experiment was performed. The details of this experiment can be seen in Chapter 4, Section 4.9. Below is a plot similar to that of Figure 6. This figure shows the data gathered for the experiment detailed in Chapter 4, Section 4.9.

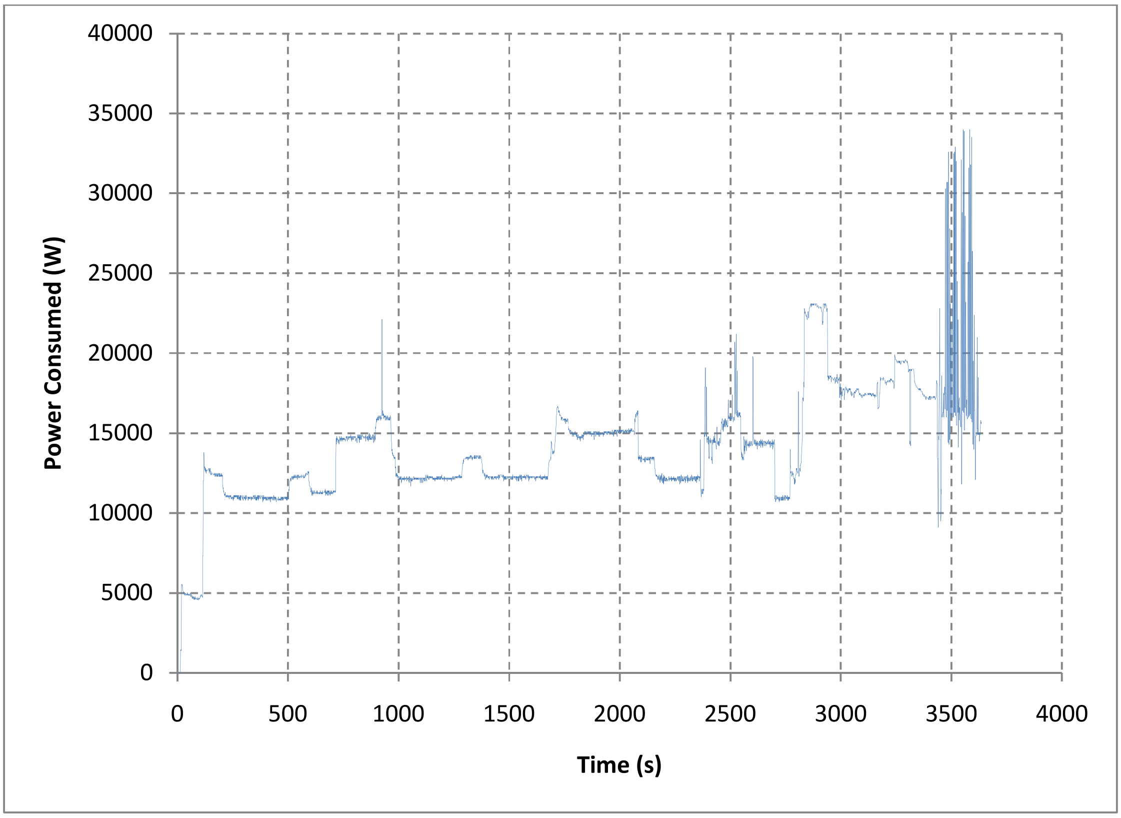

Figure 7: Power consumption results for verification experiment

A closer look at the end of the experiment helps support what Lodhia and Drake showed. The verification experiment included drilling four holes where the drill bit was pushed in and out repeatedly to foster chip removal. The plot show in Figure 8 clearly shows four distinct groups of peaks corresponding to the four drilling operations following a distinct material removal operation.

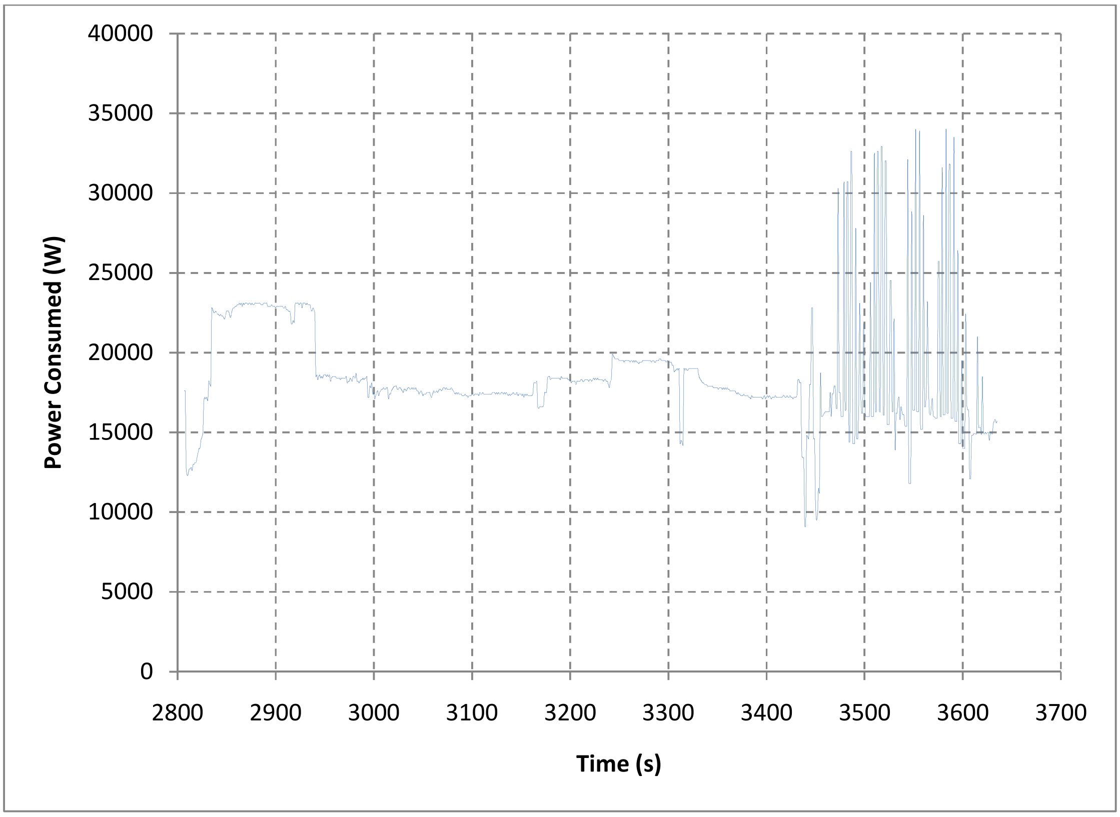

Figure 8: Close up view of milling and drilling operations for verification experiment

The repeatable, predictable peaks help support an ABC approach. The specifics and full details of the verification experiment are found in the model verification section.

3.4.2 Decomposition of a Product into an Activity Space

A manufactured product can be viewed as being composed of a series of activities or manufacturing operations required to produce that product. This definition fits into the ABC structure, but it needs to be refined to handle more complex products. A product can be defined as an assembly of smaller parts. Each smaller part can be defined by the operations that are required to produce it. The parts are joined together with some assembly operations (and perhaps some other operations) to make the final product. A graphical example of this is seen in Figure 9. The manufactured product and the unit parts behave as objects, shown in blue, while the manufacturing operations are activities, shown in red.

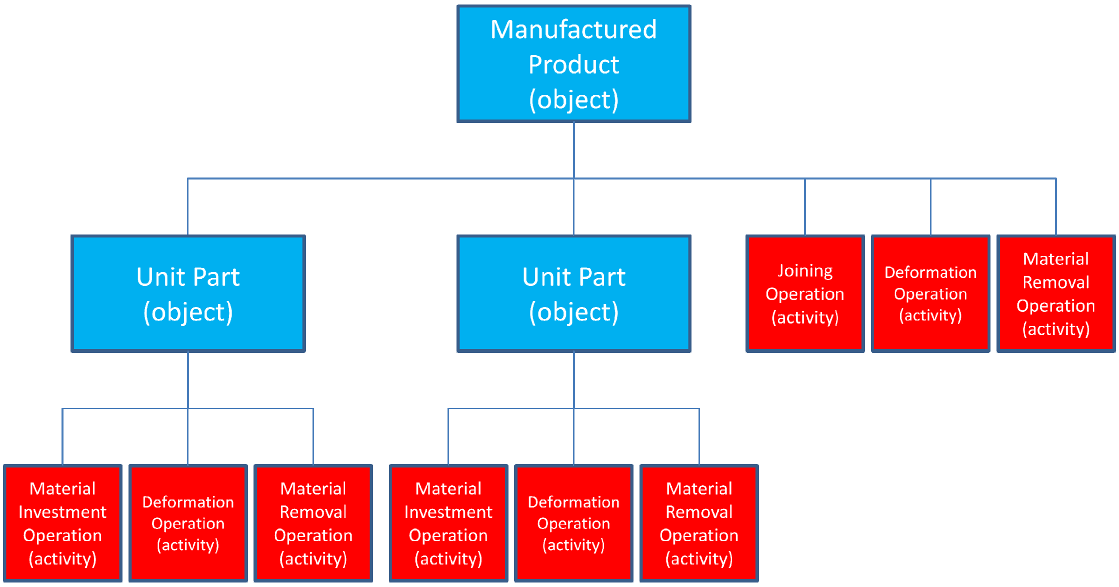

Figure 9: Simple decomposition of a manufactured product

In even more complex products, the final product can be decomposed into assemblies, each of which can be decomposed into unit parts. Ultimately, each unit part can be defined solely by manufacturing operations, and each assembly is defined by the unit parts it contains and the assembly operations needed to join them. A more complex decomposition can be seen in Figure 10.

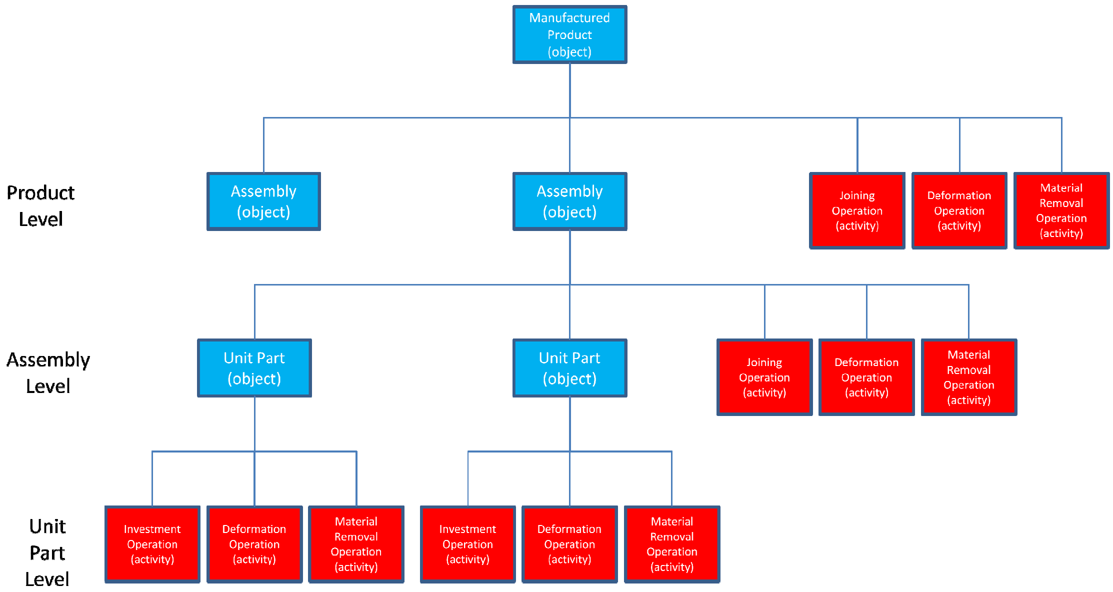

Figure 10: More complex product decomposition tree

Notice how levels are defined. The product level contains elements directly owned by the product element, while the assembly level contains elements directly owned by the assembly elements, and so on. An infinite number of levels can be added to help organize the activities required to manufacture a product. Note well that the manufactured product is still ultimately defined in terms of activities. These activities are the most fundamental elements, and are grouped into unit parts and assemblies for organizational purposes.

What starts to take shape is a multi-dimensional space of activities that define the product. So far, one dimension has been seen, and that is the part-to-whole vertical dimension of the product, as highlighted by the levels in Figure 10. The following section shows how a hypothetical product can be decomposed into a multi-dimensional Activity Space and how that Activity Space is useful. The dimensions used can be abstract as well as physical.

3.4.3 Using the Activity Space

For the purposes of illustration, a hypothetical product called Product 1 can be defined by a set of twenty manufacturing operations. The product can be decomposed into two assemblies, each of which can be decomposed into two and three unit parts respectively. The unit parts are defined by a number of manufacturing operations. A simple decomposition tree for Product 1 can be seen in Figure 11. Objects are numbered rectangles, where a numbers 1.X are the Xth assembly for Product 1, while 1.X.Y represents the Yth unit part for assembly X of Product 1. Activities are depicted as circles. (Romaniw, Bras, & Guldberg, 2010)

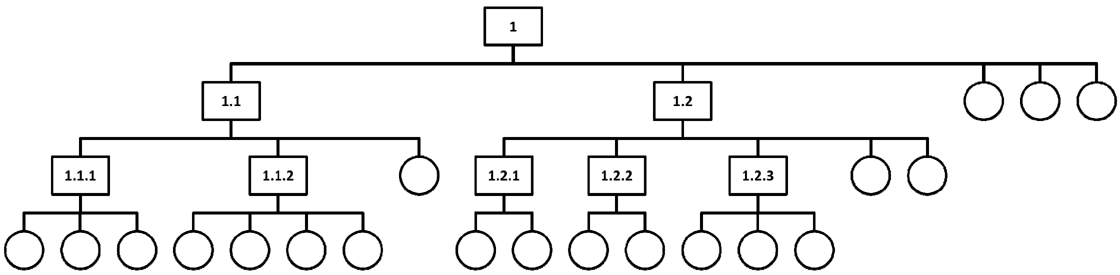

Figure 11: Hypothetical product decomposition

In the figure, it can be seen that the product is already organized vertically by level. A new dimension to the activity space can be introduced. The new dimension is a chronological sequential ordering of activities. Assuming the rule that no two activities directly belonging to a single element can occur at the same time, a two dimensional Activity Space can be defined. It is important to note that placement of objects in the activity space is not important, but placement of activities is important. (Romaniw, Bras, & Guldberg, 2010)

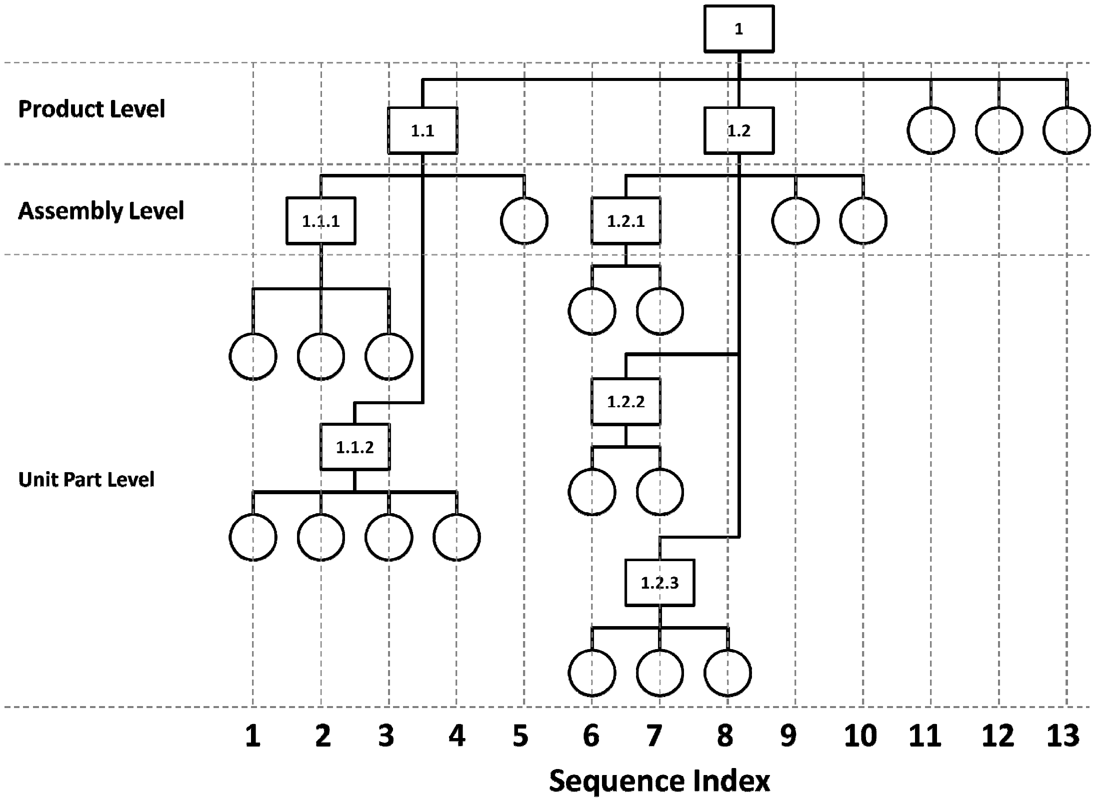

Figure 12: Two dimensional Activity Space for a hypothetical product

Another dimension that can be added to the activity space is operation class or type. Assuming six different classes of operations, the decomposition tree in Figure 12 can be refined further. (Romaniw, Bras, & Guldberg, 2010)

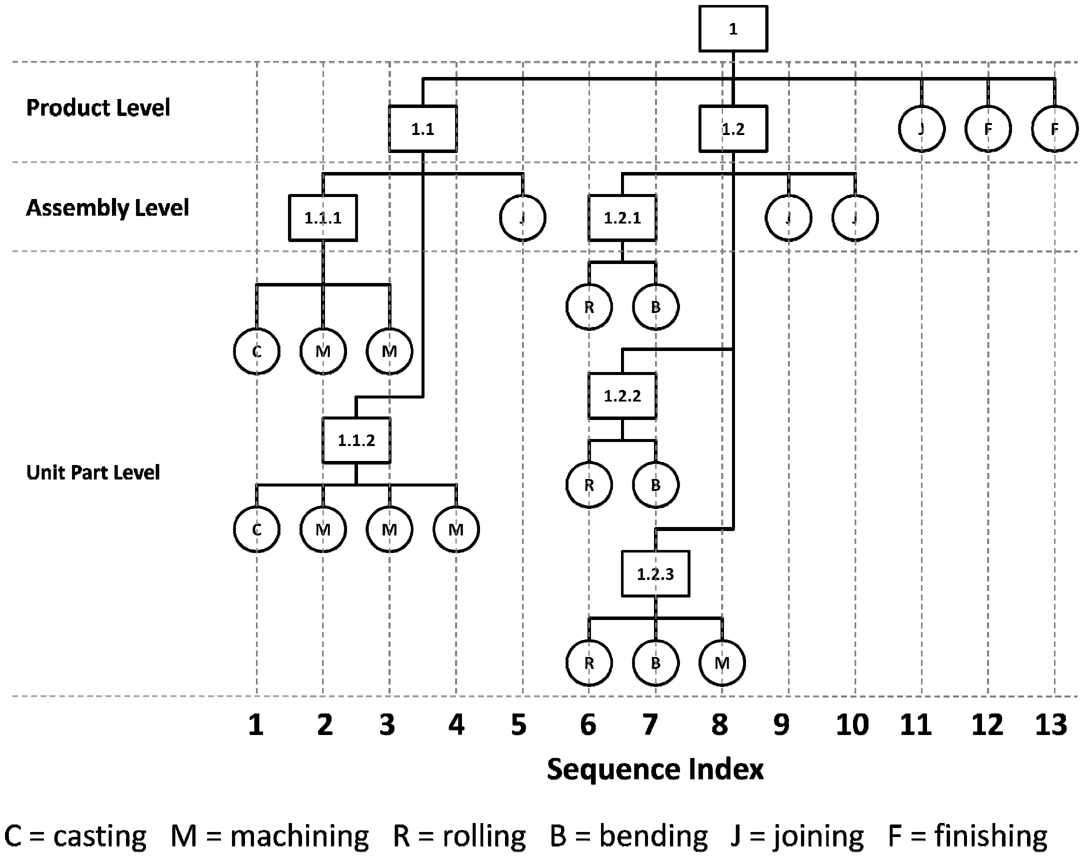

Figure 13: Three dimensional Activity Space for a hypothetical product

Adding one more dimension, the product's activities can be distinguished by the factory or plant in which they are performed. This is called the "enterprise perspective." Figure 14 shows a *four dimensional* Activity Space. The dimensions shown are product level, enterprise level, operation type, and sequence. (Romaniw, Bras, & Guldberg, 2010)

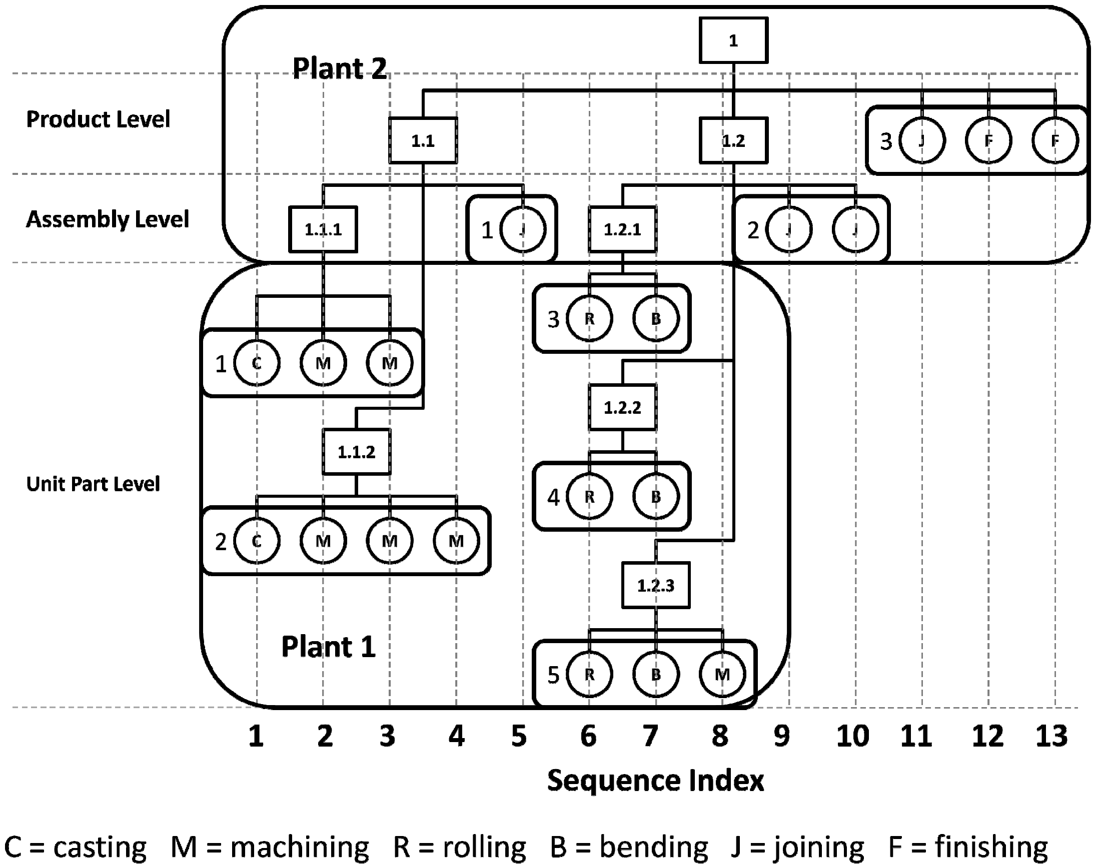

Figure 14: Four dimensional Activity Space for a hypothetical product

This is assumed to be a fully defined Activity Space for this product. Notice how the activities do not change from one decomposition tree to the next. The activities only have to be defined one time and they can be used and reused over and over based on their assignment or location. This matches well with an object oriented approach.

The product's Activity Space has four dimensions. Different types of analysis can now be performed. Isolating each dimension independently can give insight. Looking at product level can show how much it cost to build a unit part or how much it cost to build an assembly. Next, the sequential dimension can be isolated. The amount of energy consumed at time 1 can be compared to the amount of energy consumed at time 7, giving insight as to peak energy demand times. Next, cost by operation type can be calculated to determine which types of machines or what kinds of processes are consuming the most energy. Finally, cost by manufacturing plant in the enterprise perspective can be assessed to determine which plant consumes the most energy. Multi-dimensional analyses can also be performed, such as determining the machining costs for unit parts in Plant 1.

What is most important here is that the activities are not duplicated. Activities are defined once and only once and are reusable. The various dimensions help organize the system to help perform analysis from a particular perspective, so long as the activities have the appropriate attributes assigned to them. This type of structure can easily be realized in an object oriented model.

3.5 Modeling Method and Structure

As mentioned, the modeling language used is SysML. Though SysML has many types of diagrams available to model a system, only two diagrams are used in this model. The first is the block definition diagram (BDD) and the second is the parametric diagram (PAR). Structure is depicted in BDD's while PAR's represent the mathematical relationships amongst elements used to quantify costs. Though SysML can model additional diagrams, only BDD's and PAR's are used because it is a limitation of the solver ParaMagic. In accordance with the third research question, usability is improved with an off-the-shelf solver, like ParaMagic. However, this may diminish SysML's ability to represent the particular model structure required. At this time, additional diagrams are not useful. Using all available diagrams, SysML would be able to model the ABC structure desired, supporting the first research question. However, such a model may not be able to return meaningful results, diminishing support for the second research question. Using ParaMagic helps return meaningful results, but limits SysML's modeling capability. In order for the ABOOM Model to support the first research question, an ABC structure must be able to be built exclusively using BDD's and PAR's. In order to see how this is done, the way in which ABC elements from the ABOOM Model are depicted in SysML is discussed.

The fundamental unit element in SysML is the block. A block is an object that contains various properties. In particular, part properties, value properties, and constraint properties are used. Part properties are other blocks that are contained in a block in a part-to-whole relationship. Value properties are numerical values that belong to that block. Constraint blocks correspond to mathematical equations. Parametric diagrams are assigned to a particular block and show how the parts, values, and constraints interact. This is done graphically by connecting the parameter ports on a constraint block to the value properties contained in blocks or.

Manufactured products, assemblies, and unit parts (objects) are all modeled as blocks. Activities and resources are also modeled as blocks, even though this may not make initial intuitive sense. This is done for several reasons, apart from ParaMagic's restrictions on which diagrams are usable. Firstly, the ABOOM Model needs to be able to represent part-to-whole relationships so that containment of resources in activities and activities in manufacturing objects can be shown. Secondly, value properties need to be present so that the ABOOM Model can represent quantitative as well as qualitative results. Lastly, constraints are needed to represent the mathematical equations that are used to calculate values. It is important to note that blocks are objects in the object oriented sense and not the ABC sense, so it is okay to represent activities and resources as blocks.

The ABOOM Model looks at a three dimensional Activity Space. The three dimensions will be product level, operation type, and enterprise level. This is shown notionally in Figure 15 using the hypothetical product decomposed in Section 3.4.3.

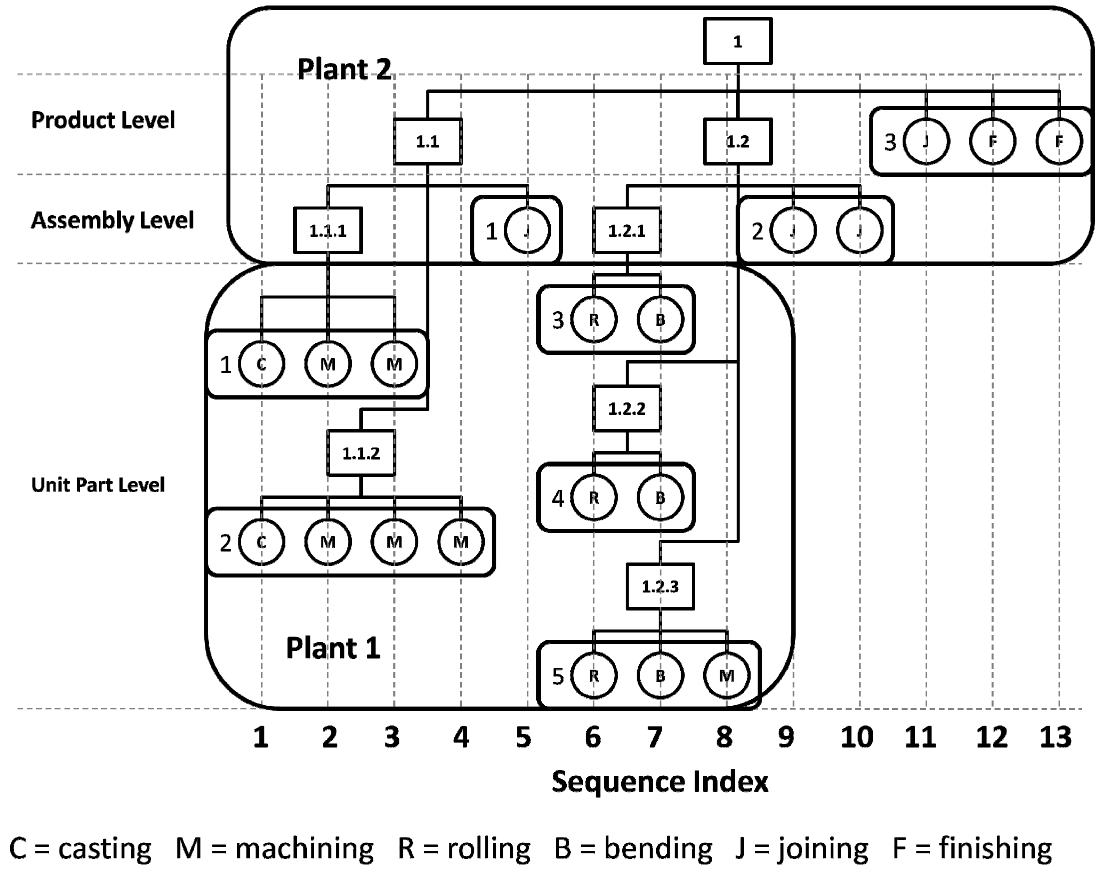

Figure 15: Graphical depiction of ABOOM Model dimensions using Hypothetical Product 1

Operation types are determined by creating a unique block for each of ten modeled manufacturing operations, each generalized to a base classifier block that represents the general attributes of a manufacturing operation. The individual operation blocks inherit all of the properties of the base classifier block and contain their own unique properties. The ten manufacturing operations modeled are shown below.

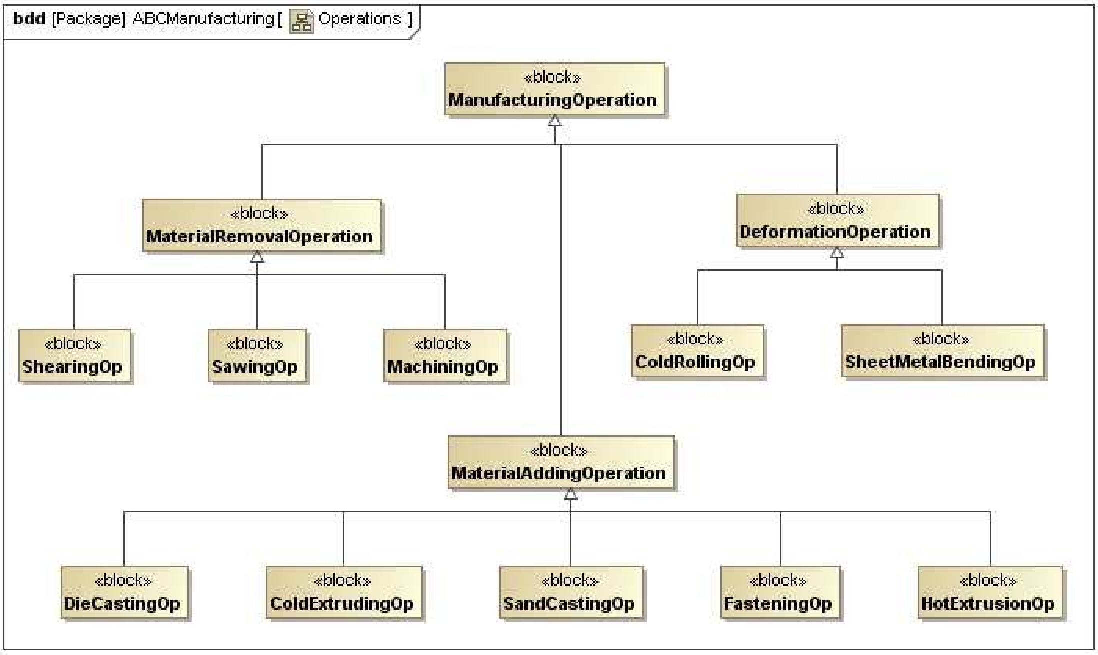

Figure 16: Manufacturing operations in the ABOOM Model

Product level can easily be created with SysML's part property attributes. Operation blocks can be referenced by unit parts, which can be assigned as part properties of assemblies, and so on. This creates a general hierarchy of elements similar to that shown in Figure 10. The object elements (product, assembly, unit part) have similar properties, so they can all be generalized as a *Manufactured Element* that defines all of their common attributes. The breakdown can be seen in Figure 17.

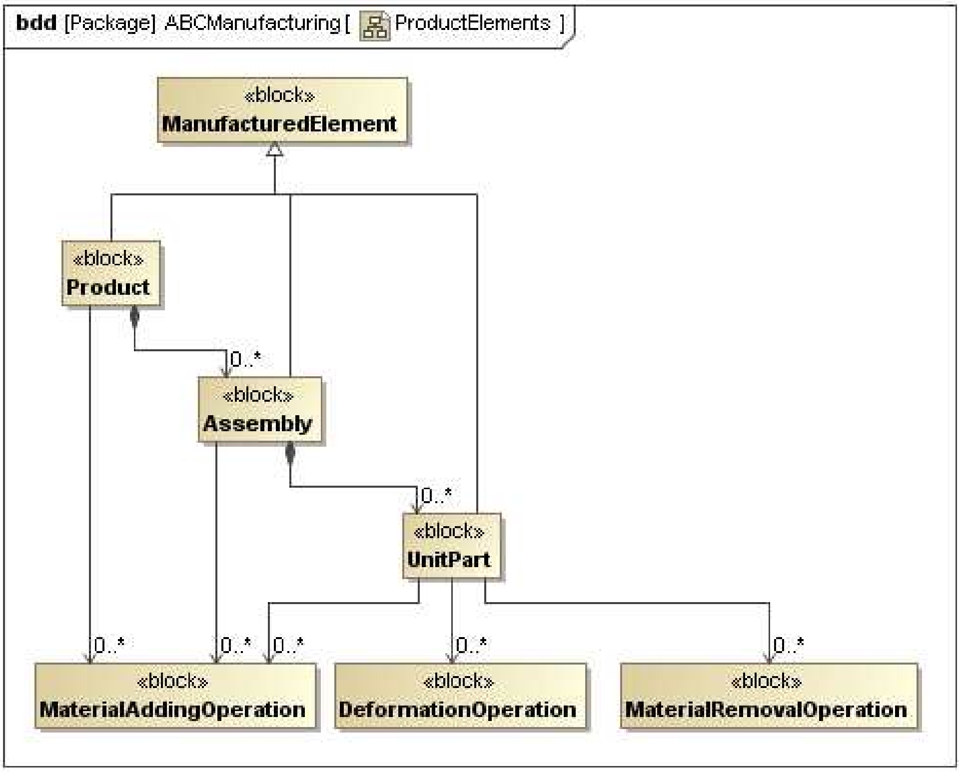

Figure 17: Product level decomposition containment tree

The enterprise level represents a series of plants that are grouped together to form a company or enterprise that manufactures products. Plants can be created the same way that product levels are created. A plant can directly contain operations as part properties, or they can be split up by multi-stage processes that are each made up of operations. In the two cases of the product level view and the plant view, the product and its sub-elements and the plant and its sub-elements all behave as ABC objects. The enterprise, plant, and process can each be defined as *Manufactur**ing** Elements*, just like product level elements are *Manufactur**ed** Elements*. A similar hierarchy of elements can be defined for the enterprise level decomposition as for the product level decomposition.

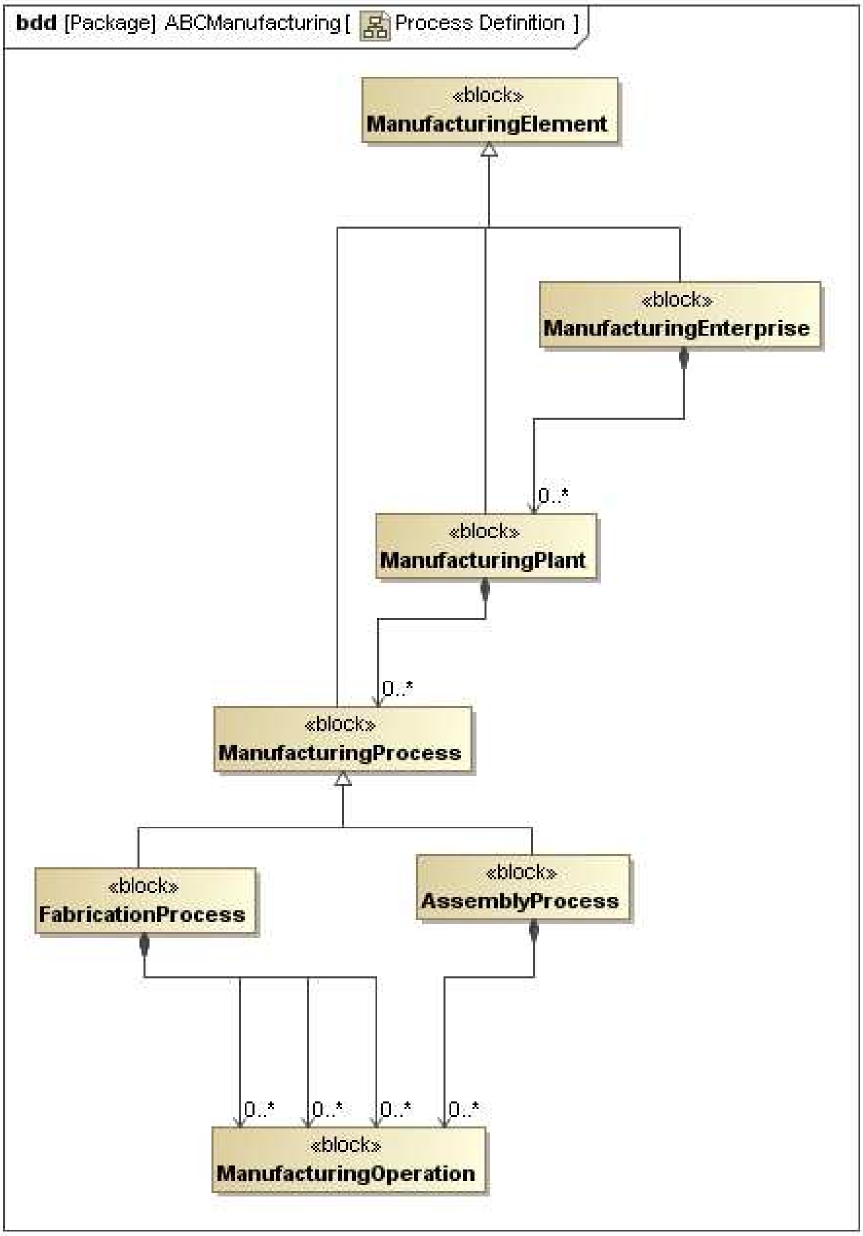

Figure 18: Enterprise level decomposition containment tree

There are five types of resources used in the ABOOM Model, three traditional and two non-traditional. Traditional resources include fuel resources, solid material resources, and liquid material resources. Fuel resources are distinguished because they provide energy and produce carbon dioxide in the process. Liquid and solid material resources are similar, but there are some physical properties unique to solid material resources and not to liquid material resources. Non-traditional resources, like machines and fasteners, are included because they behave in the same way traditional resources behave. Fasteners are essentially a special case of solid material resources. Machines are a logistical resource in that they are *consumed* by an activity for some time before being returned to the *environment* to be consumed again. It can be said that part of a machine is consumed by an activity in the form of wear and tear on the machine. The list of resources used is shown below.

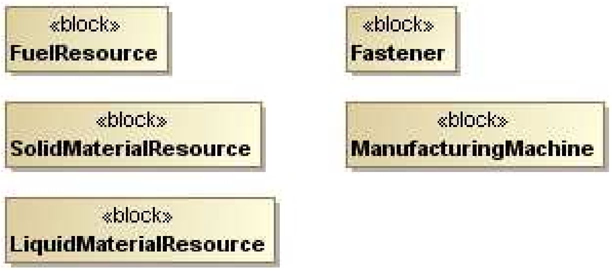

Figure 19: Resources used in the ABOOM Model

Once the structure is fully defined, an instance model is created. The instance model represents a specific case of the system. The instances are filled in with actual numbers and actual elements contained in a particular scenario. Some elements in the instance model can be made ahead of time and stored in a library. Resources can be instantiated ahead of time and stored in a library. Resources may change slightly from scenario to scenario, but a generic list of common resources can be created and stored ahead of time in a generic LCI library, comparable to traditional LCI databases. Other instances must be created uniquely for each scenario.

3.6 Methods for Data Gathering and Validation

For pre-determined resource LCI's and libraries, instance information can be derived from existing LCI's and databases. Many databases already exist that store properties of some generic fuel and material resources. Instances of some of these were created in the model. New ones can easily be created and the information to fill the instance can be derived from existing databases and LCI's.

There are several cost drivers for the ABC model that are user inputs. Amongst these are operation duration or time, a machines power consumption, volume of material melted or removed, etc. These can be determined a number of ways. Some inputs can be determined empirically by measuring properties of existing processes. Others can be estimated by skilled users. Some inputs can be derived from software, like volume and mass data from CAD files or operation time information from CAPP files. Some values can be approximated as zero to help achieve a theoretical minimum.

The model can be empirically validated, as is the case with some components of the model in this thesis. The model is based on mathematical models, which are derived analytically from a combination of physical principles and statistical data. A hypothetical scenario can be built in SysML and results can be calculated through ParaMagic. Then the results can be compared to empirically gathered information about the process. If the two results are reasonably similar, then the model is assumed valid.

3.7 Creating a Federated Model

A federated model includes information from multiple disciplines and represents multiple aspects of the system. Typically, different lower level models representing the system from a particular perspective are combined into one larger model that helps eliminate redundant information and helps tie multiple disciplines together. Some elements that different disciplines may be interested in for a manufacturing system can be a manufacturing bill of materials, an order of operations for process planning and scheduling, and material flow models for logistical analysis. Process planning engineers, logistics engineers, and manufacturing engineers all operate in the same manufacturing system, but the detailed information they are interested can be unique to their perspective.

The Activity Space breakdown from the product perspective essentially represents a manufacturing bill of materials. A product is decomposed into more fundamental elements. Each element references operations for which essential resources are defined. Additionally, the Activity Space indicates a process plan order of operations with the chronological organization of operations as indicated by the sequence index. From this, a logistical flow of materials can be defined for a system.

This thesis briefly discusses how a federated model can be created in SysML, and what such a model looks like for two case examples. Creating a federated model is not the primary focus of this thesis, so detailed definition of such a multi-disciplinary model is considered outside of the scope of the thesis. Nevertheless, this thesis explores the capabilities of SysML, so some discussion on first steps toward a federated model is present.

3.8 Conclusions About Using an Activity-Based Costing Approach

Activity-based costing is capable of representing a manufacturing system. Activity-based costing has been around for a long time, so it is capable of returning meaningful results if used properly. This supports the second research question. There are some limitations elsewhere in the approach, though.

Determining how to implement an ABC structure with SysML can be tricky. Intuitively, SysML would represent an ABC model using Activity Diagrams. However, this is not the case when using MagicDraw SysML due to the limitations of ParaMagic with respect to understanding and utilizing Activity Diagrams. If ParaMagic is assumed to be the solver, then SysML can only represent ABC models with BDD's and PAR's. This is not a bad thing, since ABC models require properties that are best represented in BDD's and PAR's, such as containment, values, and mathematical relations. Since SysML blocks can show containment, values, and mathematical relations, it is actually preferable to model ABC elements as blocks rather than SysML activities. This means that ParaMagic can be used as a solver for MagicDraw SysML, and SysML is capable of modeling the ABC structure needed for the ABOOM Model. The first research question is thus far supported.

4 SysML Model

4.1 Chapter Overview

This chapter discusses the actual ABOOM Model as it appears in MagicDraw, built with the modeling language of choice, SysML. The chapter begins with listing the requirements or criteria the model must satisfy in order to help answer the three research questions from Chapter 1, Section 1.7. Next, the chapter defines the outputs or cost elements that are returned by the ABOOM Model once it is executed. Then, Sections 4.4 - 4.7 defines in detail the actual elements created in SysML, along with their appearance, properties, structure, and behavior. Section 4.8 goes on to describe what elements can come pre-defined in the model, essentially defining an LCI database that can be made ahead of actual scenario modeling. In Section 4.9, the chapter discusses validation of the model's evaluation criteria defined in Section 4.2. Section 4.10 discusses how the federated model from Chapter 3, Section 3.6 can be created in SysML. The chapter finishes with a discussion on the SysML model and how the ABOOM Model answers the three research questions asked in Chapter 1, Section 1.7. Specifically, this chapter looks at whether or not (and if so, *how?*) can an ABC model be built with SysML, and whether or not the model can return meaningful results (first and second research questions).

4.2 Model Requirements

The purpose of the ABOOM Model is to help perform an LCI on a manufacturing system in greater detail than can be found in more general LCA's. The ABOOM Model must take in information about a manufacturing process and compute environmental burdens produced by that process. The quantified environmental burdens are assumed to be the ABOOM Model's outputs, while information about the manufacturing process are the inputs.

To positively answer the first research question of whether or not SysML can realize an ABC model structure, the ABOOM Model must be able to completely represent all of the required ABC elements, and their corresponding properties, attributes and behaviors in SysML. Though information can be extracted from outside sources, the SysML model itself should ultimately be able to contain all of the structural and numerical information.

The second research question indicates that the ABOOM Model should return meaningful results. This can be tested with model validation. If the ABOOM Model is deemed invalid, then it is assumed the ABOOM Model cannot return meaningful results. The ABOOM Model must meet three criteria in order to be considered valid:

1) The model must not violate any physical laws without appropriate assumptions
2) Decision making between elements must be non-trivial
3) The final results of a simulation of the model must be reasonably accurate

Physical laws include conservation of mass and energy, and other fundamental laws. Simplifying assumptions can be made to make a system easier to understand or easier to analyze. Non-trivial decision making means that given two non-identical alternatives, inputs for these alternatives should be such that simulation of the model should provide two distinct results. The third criterion indicates that the numerical results of model simulation must be within an acceptable error margin when compared to empirically gathered results. What qualifies an acceptable error margin is covered in the model validation section.

Apart from defining instances, the user should not have to modify the fundamental structure of the ABOOM Model. This means that PAR's and BDD's that do not include instances do not need to be modified by the user. Only BDD's that contain the instance structure need to be modified. The entire structure of the model must be available to the user so that changes may be made as desired in specific circumstances.

4.3 Model Outputs

The model's inputs can vary from scenario to scenario. Structurally, the instance model remains unchanged, but the quantitative values within each instance can change. For instance, for a material removal operation, the material removal rate (MRR) is given as the volume removed per unit time. The user may know the volume removed and the operation time, and using these as inputs can get the MRR. In a different scenario, a user knows an optimal MRR and knows the volume to be removed, so the unknown is operation time which becomes a model output.

Depending on the perspective used, the model generates different outputs. These outputs are the quantified environmental burdens relevant to that perspective, associated with the elements included in that perspective. The product level perspective and the enterprise perspective are the two perspectives represented in the ABOOM Model, and each has different outputs.

For the product level perspective, there are eight outputs or results that are quantified, listed below.

- manufacturing carbon dioxide
- embedded carbon dioxide
- manufacturing energy
- embedded energy
- primary waste mass

- secondary waste mass
- combined waste mass
- product final mass

The first environmental burden quantified is carbon dioxide, and it is split into manufacturing and embedded carbon dioxide. The second burden quantified for a product is the energy, also divided into primary and embedded energy. Next is waste mass, which is divided into primary waste mass which comes from excess material resources used directly in the product, and secondary waste mass that is produced from materials not appearing in the final product. The waste masses are combined into a single mass quantity to give a total load of waste produced by manufacturing the product. The product's final mass is given to give perspective on the amount of waste mass produced.

For the enterprise perspective, a similar list of outputs is generated. Just like for the product level perspective, the outputs for the enterprise perspective quantify environmental burdens associated with the enterprise. The list of outputs associated with the enterprise perspective is given below.

- manufacturing carbon dioxide
- manufacturing energy
- manufacturing waste mass

The list of outputs from the enterprise perspective is limited to the three burdens produced by manufacturing alone. This is because it is assumed a manufacturing enterprise is primarily concerned with the costs associated solely with its operation, rather than the overall burdens associated with its products. Embedded costs are assigned as properties of an individual product and are not associated with overall enterprise operations. Furthermore, waste mass is not broken down into primary and secondary waste mass. It is assumed that an enterprise does not perform its own waste processing, and all waste mass is shipped out in bulk to a third party processer.

With these outputs, the ABOOM Model is able to provide insight about the costs associated with a single complete product as well as an enterprise that may contain processes for multiple products.

4.3.1 Energy

According to Figure 4, energy is consumed by a system. Energy can also represent an output. In a manufacturing system, energy is required to deform material. Through conservation of energy, this energy is ultimately converted to light energy or heat energy by friction. Calculating the amount of energy put into a system can indicate how much heat energy is generated by a system. The more heat generated, the greater the demand on climate control systems for a factory. The greater the demand on climate control systems, the more energy is required to maintain a required ambient temperature. This leads to a cascading effect. Knowing the maximum energy put into a system can help a designer size and estimate costs for climate control systems.

Specific embodied energy (also called specific production energy) is a property of a resource. For resources, this is the amount of energy embodied per unit of that resource. To get the total amount of energy embodied, the resource’s specific embodied energy is multiplied by the amount of that resource consumed.

Manufacturing energy can be broken down into three parts. The first part is the theoretical amount of energy required to produce a feature, assuming perfectly efficient and ideal machinery. The second part is the base energy. This reflects any continuous, time dependent energy consumption by the system. On a typical manufacturing machine, base energy reflects energy needed to run lubricant pumps, lights, vacuums, and so on. The third part of the manufacturing energy is the transient energy consumed by a process. Transient energy would reflect inrush currents to start motors, machine warm up, and so on. Transients are one time, fixed amounts of energy consumption. To illustrate these three parts of the total manufacturing energy, a portion of Figure 6 has been modified below to show only the machining of the L-shape of the part in Figure 5. (Lodhia & Drake, 2008)

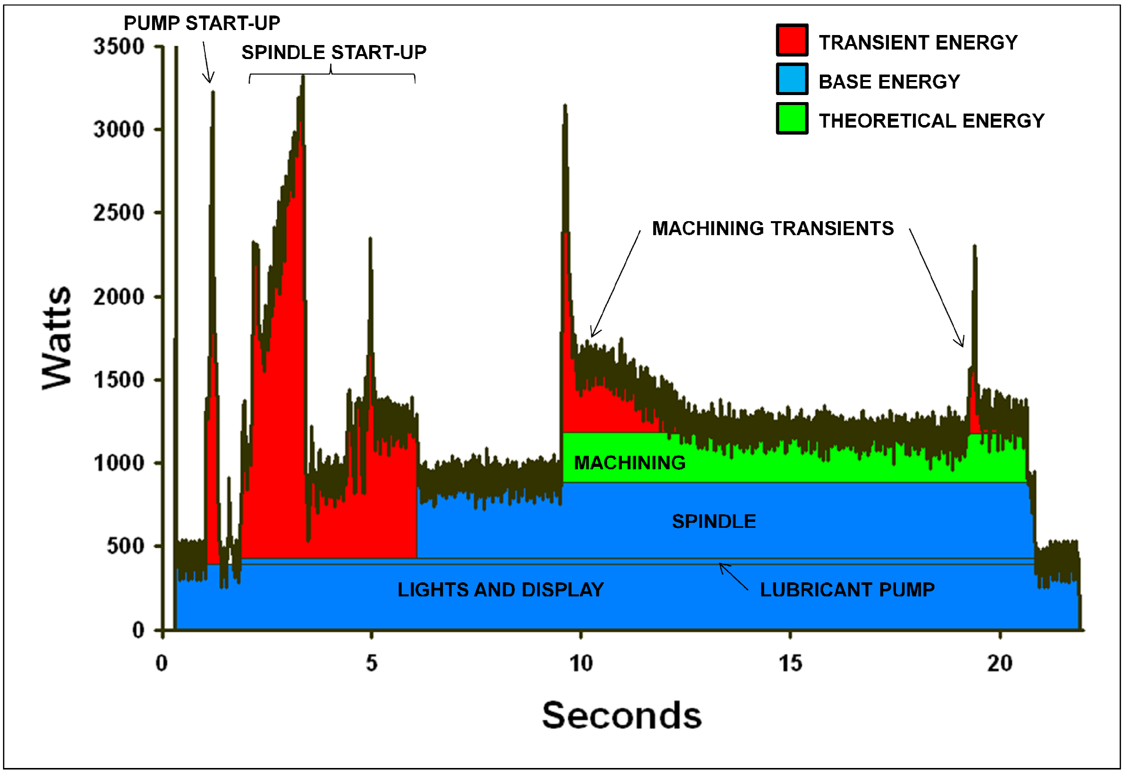

Figure 20: Modified power vs. time plot for a sample part

It becomes clear that the theoretical energy makes up a fraction of the total energy consumed during an operation. Including base energy and transient energy adds fidelity to the model. Though transient spikes can be difficult to measure or quantify, base energy is relatively easy to quantify since it is based on a steady power consumption that can be easily determined. To further correct the model, the theoretical energy is adjusted by a machine efficiency factor. Adjusting the theoretical required energy reflects that a machine inefficiency in producing a feature. More energy was consumed by a machine than theoretically needed to produce a specific feature (assuming an otherwise ideal machine, where transients and base energy are zero).

4.3.2 Carbon Dioxide

Carbon dioxide is a greenhouse gas that negatively impacts the environment. It is important to know how much carbon dioxide is being produced by a system in order to determine that system's carbon footprint. Knowing a system's carbon footprint helps determine effectiveness of carbon offsets and whether the current carbon offsets are adequate or not.

Embodied carbon dioxide is similar to embodied energy in that it is the amount of carbon dioxide produced in harvesting a resource. Embodied carbon dioxide is calculated by looking at a resource's specific embodied carbon dioxide (or specific production carbon dioxide) and multiplying that by the quantity of the resource consumed.

Carbon dioxide is produced by consuming fuel during an operation. Each fuel resource has a specific carbon dioxide emission quantity associated with it. This amount reflects the mass of carbon dioxide produced in consuming enough fuel to produce a unit of energy. To determine the total carbon dioxide produced during an operation, the energy specific carbon dioxide rate for a fuel is multiplied by the amount of energy that fuel provides. The amount of energy a fuel provides is equal to the manufacturing energy of an operation. For simplicity in this model, it is assumed that only a single fuel is consumed by one machine during an operation.

4.3.3 Waste Mass

Waste is produced during a manufacturing process. Waste can be processed two ways. The first is that it can be dumped in a landfill, where it is a negative environmental impact. The second way is that the waste can be recycled, which requires more resources. Though recycling is often better than harvesting virgin resources, it still impacts the environment. The best solution would be to minimize waste mass in the first place.

Waste mass cost is divided into two parts. The first is primary waste mass and the second is secondary waste mass. Both costs are incurred during the manufacturing process. Due to the complexity of resource harvesting, refining, and purifying processes, embodied waste mass is excluded. Primary materials are found in the final product, so primary waste mass represents the excess material that was consumed but had to be removed to create a final product. Secondary materials are auxiliary materials that are consumed during the manufacturing process, but do not appear in the final product. Examples of secondary materials are sand in a sand casting mold, coolants and lubricants used during machining, cleaners, solvents, etc.

Primary mass can be both added and removed from a product. Secondary mass is always considered waste. Waste mass totals assume no in-house recycling or reclamation of material. Waste mass totals are meant to reflect an amount of mass that needs to go to post-processing where it is recycled or dumped in a landfill.

4.4 Basic Model Elements

4.4.1 Value Types

Value types define attributes of a value property. Specifically, value types give the units and dimensions of a value property. Value properties are used not only to assign units, but to ensure consistency within the model. This is seen most clearly in PAR's, where SysML will not allow a user to connect one value type to a constraint parameter of a different value type. This helps uphold the first criterion by ensuring proper units during calculation. All of the value types used are generalized as real numbers by the base classifier value type *Real*. A complete list of the value types created and used in the model, and their corresponding units can be seen in Appendix A.1.

4.4.2 Constraints

Constraints blocks are used to define equations. A parametric mathematical equation is represented as a constraint in the constraint block. Parameters of the constraint are as parameter ports of the constraint block. Each parameter is assigned a value type to ensure model consistency. For general equations, such as $C = A + B$, the parameters are typed as real numbers. Since all of the value types in the model are also real, all of them can be connected to parameter ports typed as real. A complete list of all of the different constraint blocks created and used in the model are given in Appendix A.2.

4.5 Resources

4.5.1 Fuel Resources

Fuel resources represent energy providing resources. The generalized fuel resource block can be seen in Figure 21.

Figure 21: Fuel resource block

Each fuel resource has three value properties. On the left hand side of the colon for the value properties is the name of the property. To the right of the colon is the type. These types correspond to the lists of value types shown in Appendix A.1. The first value property, named *specificCarbonDioxide*, represents the mass of carbon dioxide release per unit of energy provided. In this model, it is given in units of kilograms of carbon dioxide the fuel releases for every joule of energy it provides.

The second two properties are the production energy and carbon dioxide. These represent the amount of energy and carbon dioxide consumed or released during the production or harvesting of a quantity of that resource that is capable of providing a unit of energy. This would be the joules of energy consumed in order to create an amount of a fuel resource sufficient to produce one joule, or the kilograms of carbon dioxide released in order to create an amount of fuel sufficient to produce one joule.

An example is diesel fuel production in Sweden. While combusting enough diesel to produce 1 MJ of energy, 74.6 g of carbon dioxide are released, representing the *specificCarbonDioxide*. About 1.25 MJ of energy is consumed and 10.4 g of carbon dioxide are produced and released to produce that quantity of diesel.(CPM)(Shapouri, Duffield, & Wang, 2002) An instance block representing this example of a fuel resource can be seen in Figure 22.

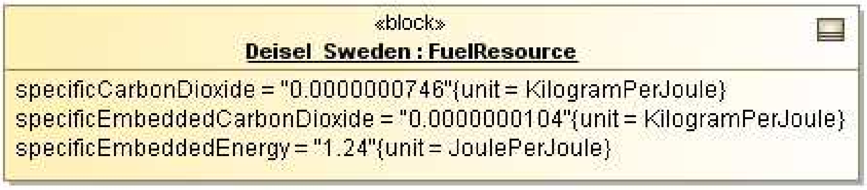

Figure 22: Fuel resource example of diesel produced in Sweden

Figure 22 is an instance block representing an instance of a fuel resource. Its properties are defined by the base classifier block for a fuel resource seen in Figure 21. The base classifier block defines the elements properties and property type, while the instance block contains actual numbers associated with that particular instance. Notice that the name of the instance block, shown as *Diesel_Sweden:FuelResource*. This indicates that the name of the instance is *Diesel_Sweden*, and that it is of the type *FuelResource*, as defined by the block in Figure 21. The name is arbitrary, merely helping to distinguish the instance from other instances. Since the information for many fuel resources already exists in LCI databases, a library of fuel resources can be made before the user begins instantiating a scenario.

Electricity is considered a fuel resource because it provides energy to a system. The specific production carbon dioxide would reflect the emissions produced in order to provide a unit of electrical energy. Traditional electrical resources would have a non-zero quantity for this slot since other fuels are burned to create electricity. Alternate energy resources should have a small value, or zero for this slot. Specific production energy is zero in an ideal case, but can reflect inefficiency and losses in providing electricity. For instance, for every joule of energy provided to a system, a 25% of a joule was lost due to generator inefficiency or line losses. This number can vary depending on where and how the electricity is produced and consumed.

4.5.2 Material Resources

Material resources used in this model are of two types: solid and liquid. This distinction is made because certain properties are specific to a material in the solid phase, while others are specific to a resource in the liquid phase. The two material resource blocks can be seen in Figure 23.

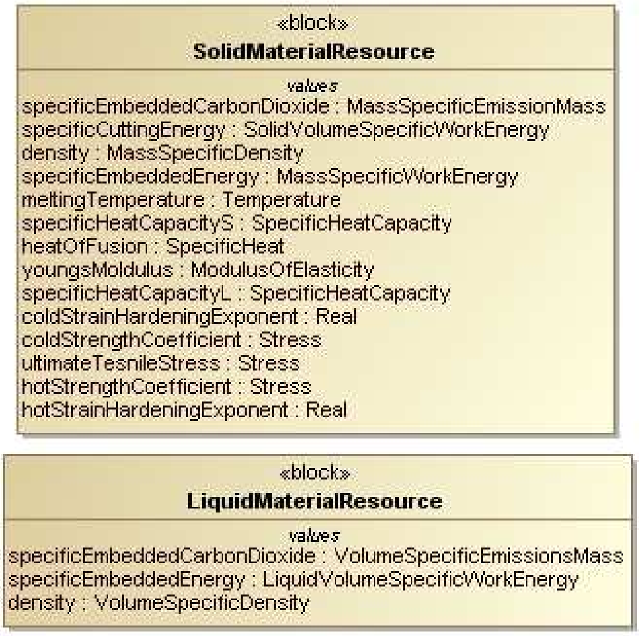

Figure 23: Blocks representing solid and liquid material resources

Both solid and liquid material resources have production energy and carbon dioxide. As with the fuel resources, this is the amount of energy and carbon dioxide required to produce a quantity of that resource. For solid material resources, this represents the energy and carbon dioxide consumed and produced, respectively, per unit mass. For liquid material resources, this represents the energy and carbon dioxide consumed and produced, respectively, per unit of fluid volume. Other value properties are basic material properties. Notice that the solid material resource contains far more value properties. This is because most calculations for the manufacturing operations considered required the physical properties of a material that is primarily in the solid state.

Solid material resources primarily describe metals, while liquid material resources are used to describe coolants or lubricants.

4.5.3 Machine Resources

It may seem like manufacturing machines are not resources, but rather objects or special objects. In the way that machines are used in this model, they are closer to resource or cost drivers. Machines determine at what rate fuel resources and material resources are consumed. In certain circumstances, a machine can be considered a pure resource. One such situation would be if scheduling was taken into account. In this case, a machine would be a resource *consumed* for a period of time, before becoming available again. The machine resource would only be able to be consumed a limited number of times before it became used up and needed to be replaced, usually through some sort of maintenance or part replacement. For all intents and purposes in this model, a machine is a resource.

The block for a machine can be seen in Figure 24.

Figure 24: Machine block

The block contains two reference properties: the fuel resource and lubricant used by the machine. Lubricant is a liquid material resource, and it is assumed that this can also represent a coolant. In many machining operations, the coolant and lubricant are mixed as one, so they are used interchangeably.

The value properties reflect cost drivers. Lubricant flow rate is the volume of lubricant consumed per unit time, while the lubricant recovery rate indicates how much of that lubricant is recovered and not lost to waste. The base power is a continuous, time dependent energy consumption rate used to calculate the base energy. Transient energy represents the one time energy committed to performing discontinuous, discrete quantities of energy. These transients represent energy consumed during machine warm up, energy used to bring a spindle up to speed, the energy required for axis movement, etc. Some of these transients can be clearly identified in Figure 6. Efficiency factor is used as an adjustment to the operation energy, showing how much more energy a machine needs to provide so that a required useable amount is achieved.

4.5.4 Fasteners

Fasteners may seem like they should be treated as objects, and in some cases they can. As a simplifying assumption, the manufacturing process of a fastener is excluded from this model. As a result, fasteners behave like resources rather than objects. When used in the model, they tend to behave as a special case of a solid material resource. Energy and carbon dioxide required to produce an individual fastener is considered negligible, since some fasteners are manufactured in large batches. Only the production costs of the material used in making the fastener are considered. The fastener block can be seen below.

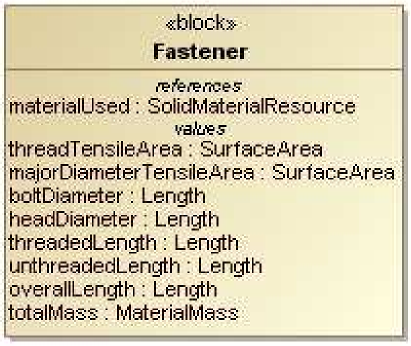

Figure 25: Fastener block

This particular fastener is assumed to be a machine screw or threaded bolt, hence the value properties associated with the block. This block is equally capable of representing a rivet as well as a bolt. This is done simply by making the threaded length equal to zero, and the thread tensile area equal to unity. These terms will drop out of the fastening energy equations. For blind mandrel rivets, the preload applied is the mandrel breaking force.

4.6 Activities

4.6.1 The General Manufacturing Operation

All manufacturing operations have several properties in common. There are a total of fourteen of these properties. The ten manufacturing operations defined in the ABOOM Model, originally shown in Chapter 3, Section 3.5, Figure 16, are all generalized as a *manufacturingOperation*, so they each inherit all fourteen properties. Each specific manufacturing operation defines additional properties unique to that operation in their specific block. The ten operations defined in this model represent one dimension of the Activity Space: grouping activities by type or class.

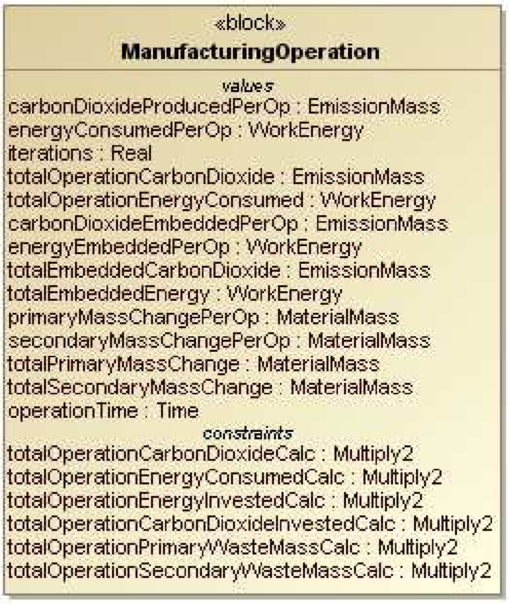

Figure 26: General manufacturing block base classifier

The first six values associated with a manufacturing operation are on a per-operation (-*perOp*) basis. These are the costs associated with performing the operation a single time. The six –*perOp* costs that are calculated are the carbon dioxide produced, energy consumed, embodied energy, embodied carbon dioxide, primary waste mass, and secondary waste mass produced. These correspond to the costs associated with the product level decomposition, described in Section 4.3. The next value is the number of iterations, representing the total number of times the identical operation is carried out. The next six values are the total costs associated with the six –*perOp* costs, but totaled over all the iterations. The total costs are essentially the costs –*perOp* multiplied by the number of iterations. This is shown in the manufacturing operation block's PAR in Figure 27. The PAR diagram is associated with the block definition of a manufacturing operation, seen in Figure 26, and represents the behavior and relationships of some of the elements of the manufacturing operation. Additional behaviors are defined in other PAR diagrams. Finally, the operation time or duration is defined in the manufacturing operation base classifier.

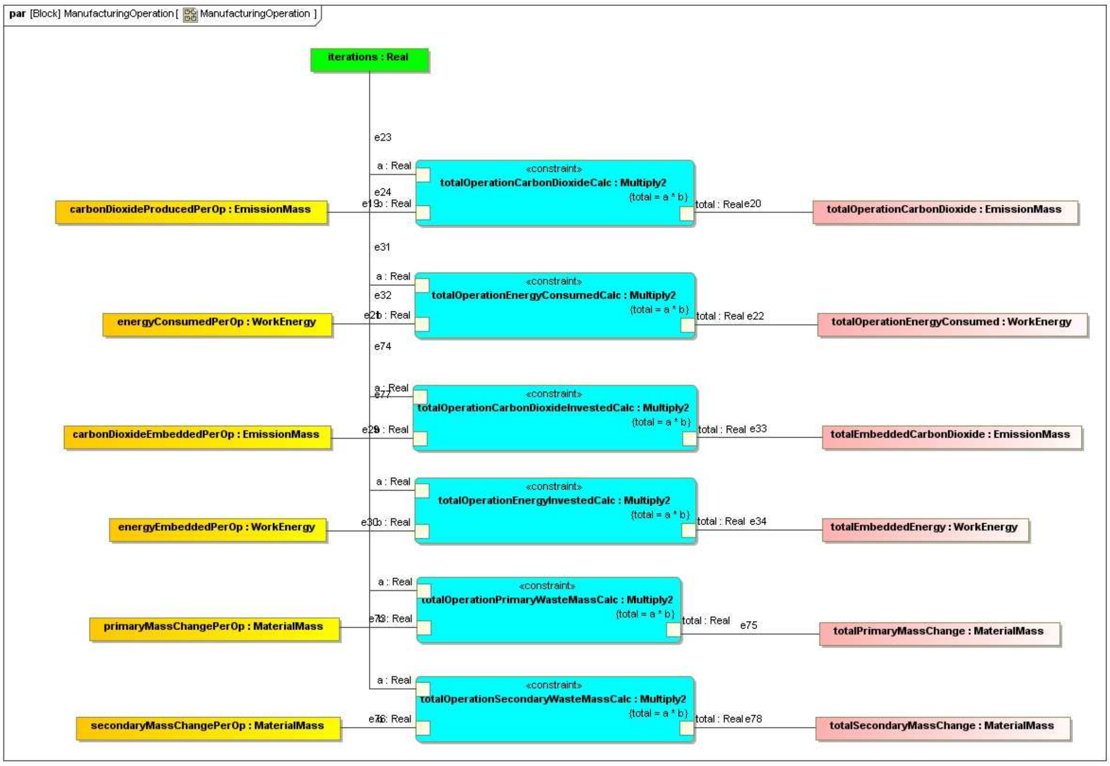

Figure 27: Manufacturing operation parametric diagram

There are three general groups of manufacturing operations. The first group consumes primary material and adds it to the product (material adding operation), the second group neither adds nor removes material (deformation operation), and the third group removes material from the product (material removal operation). These three groups are discussed in the following sections.

The ten manufacturing operations modeled in the ABOOM Model contain additional properties to those shown for the manufacturing operation base classifier. These can all be seen in detail in Appendix A.4. In addition to the value properties common to all manufacturing operations, the individual operations contain value properties particular to that operation. For instance, a machining operation inherits the properties of the manufacturing operation, but additionally defines a *volume removed* value property. Furthermore, each individual manufacturing operation contains the material resource being consumed by the operation as well as the machine resource that is performing the operation. Both are modeled as part properties to the individual operation block. Some operations may consume more than one material resource, and this is specified in each block in Appendix A.4. It is assumed that each operation is performed by only one machine, but this is left a property of the individual operations and not the base classifier because this may not always be the case.

Material being consumed by the operation is attributed to the operation and not to the product (which would seem like the logical choice) because the model is trying to adhere to the ABC structure where resources are allocated to activities, not directly to ABC objects.

4.6.2 Material Adding Operations

Material adding operations consume raw primary material resources and add them to the product. Five material adding operations were created in this model:

- die casting
- sand casting
- cold extrusion
- hot extrusion
- fastening

The first four material adding operations are generally used to define the basic shape of a product. Fastening adds material in the form of fasteners.

Total embodied costs for the operation are composed of the embodied costs for the primary material (or fastener) added, the secondary resources used, and the fuel used. Primary mass change for each of the operations is also added to the final mass of the product and does not go to primary waste mass. Secondary mass change for each of the operations contributes to secondary waste mass.

4.6.3 Deformation Operations

Deformation operations do not add or remove material from a product. These operations change the shape of the product, but total part mass remains unchanged. The two deformation operations modeled are given below:

- sheet metal bending
- cold rolling

Total embodied costs for the operation include embodied costs in the secondary resources used and the fuel used. There is no primary mass change for these operations, so there is no embodied cost associated with primary mass change. Secondary mass change goes to secondary waste mass.

4.6.4 Material Removal Operations

Material removal operations remove primary material from the product. The three material removal operations modeled are listed below:

- sawing
- shearing
- machining (removal by chip formation alone)

Total embodied costs for the operation include embodied costs for secondary material used and fuel used. Primary materials removed do not remove embodied costs from the total embodied costs from the product. This is because that amount of material was at one time consumed to create the product, and even though it does not appear in the final product, embodied costs would have been paid. Both primary and secondary mass changes contribute to their respective waste mass total.

4.7 Objects

4.7.1 Product Element Objects

To add a dimension to the activities in the Activity Space, a product level decomposition is modeled. It is assumed that a typical product is decomposed into assemblies. Each assembly can be decomposed into unit parts, which in turn are decomposed solely into activities. Products contain assemblies and reference joining operations, like the fastening operation modeled. Assemblies, likewise, contain unit parts and reference joining operations like the fastening operation. Products, assemblies, and unit parts behave as ABC objects. All manufacturing operations are generalized by the same base classifier, so a general hierarchy of elements can be constructed. The hierarchy is shown in Figure 28. Since there is not strict limit as to how many assemblies a product can be decomposed into, or the number of operations a unit part can reference, the multiplicity of each of element is infinite, as depicted in the figure with the notation *[0..*]*, representing “zero to infinite” elements.

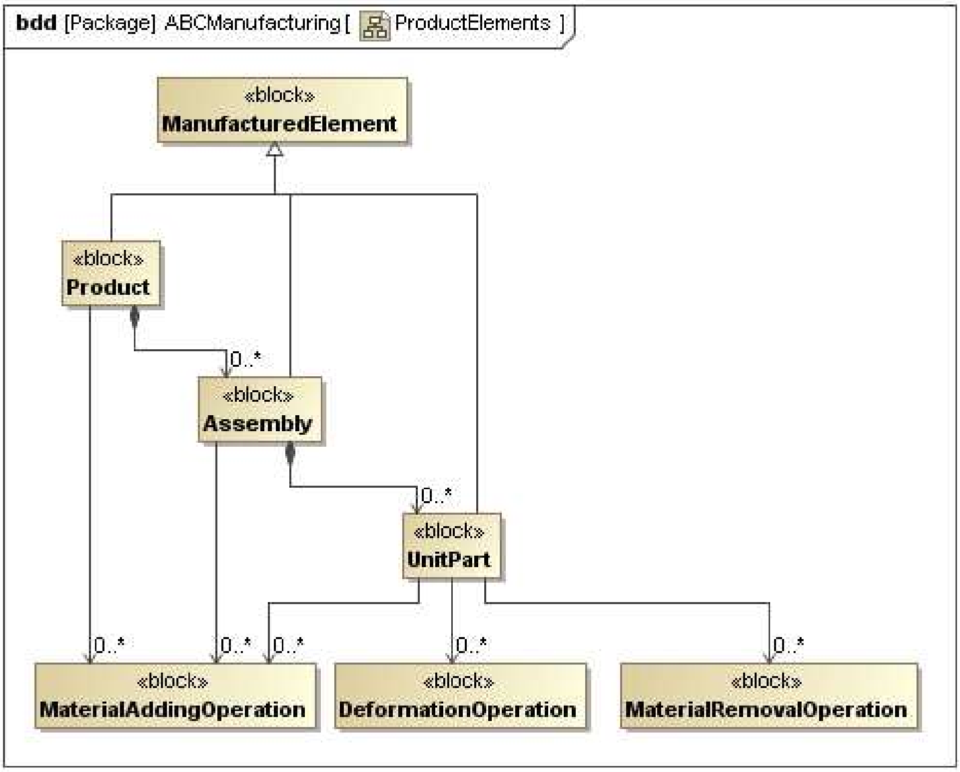

Figure 28: Hierarchy of elements from the product element perspective

Just like with activities, products, assemblies, and unit parts all have common attributes. These attributes are modeled in a generic base classifier called a *ManufacturedElement*, shown below.

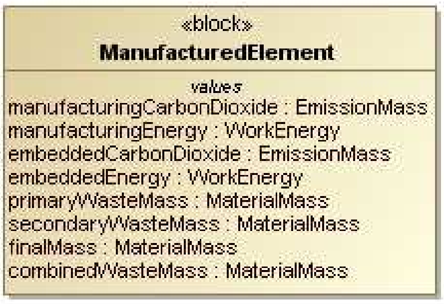

Figure 29: General manufactured element base classifier block

The eight value properties associated with a manufactured element correspond to those discussed in Section 4.3. These correspond to the various costs assumed to be of interest for a manufactured element, such as a manufactured product. The manufacturing costs help with understanding the costs associated with actual product manufacturing, while embodied costs help give a broader picture of the element's cost by giving some perspective on the relative magnitude of the manufactured and embodied costs. Splitting waste mass into two categories helps put additional perspective on the costs associated with the product. For instance, a high primary waste mass may indicate problems with part geometry and process selection, especially with material adding operations. A high secondary waste mass (which would increase with wasted lubricants, casting sand, etc.) may indicate high inefficiencies in machines or processes. For further information about the value types assigned to the manufactured element's value properties, Appendix A.1 contains a list of value types and their description.

The most basic manufactured element is the unit part, which is shown in Figure 30.

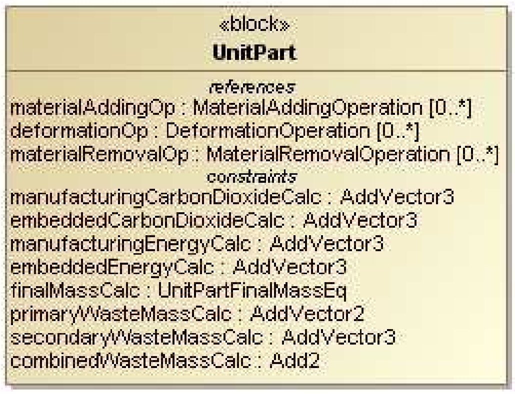

Figure 30: Unit part block

A unit part can reference any of the three categories of manufacturing operations described in Sections 4.6.2 - 4.6.5. Each of these is of the type *ManufacturingOperation*, defined by Figure 29. Generally, a unit part must reference at least one material adding operation, since material resources must be consumed to create a unit part. Nevertheless, the material adding operation multiplicity is *[0..*]* in the event of special cases that cannot be predicted at this time. The unit part block does not contain any value properties itself, but rather it inherits these properties from the manufacturing operation base classifier. What is contained in the unit part block is a list of constraints that the unit part has in addition to the constraints inherited from the manufacturing operation block. Appendix A.2 lists all of the constraint blocks with the corresponding mathematical equation the constraint type is representing. The way in which the costs from Figure 30 for the unit part are calculated can be seen in the unit part's PAR diagram.

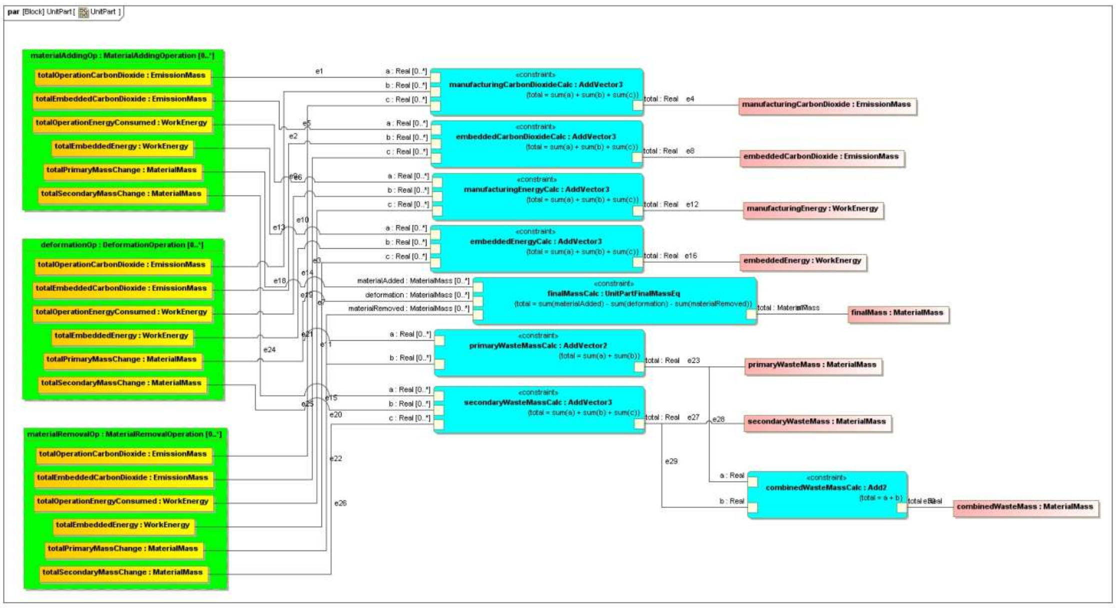

Figure 31: Parametric diagram for a unit part block

The next element in the product level decomposition is the assembly block. As mentioned earlier, an assembly can contain both unit parts and joining operations. Contained unit parts are depicted as part properties of any multiplicity. This containment indicates that the assembly block contains a unit part block, which in turn contains all of the properties associated with a unit part. Since a unit part references only manufacturing operation part properties, the assembly block can be said to ultimately reference only manufacturing operations with the unit part block merely adding organizational structure. The joining operation is also modeled as a reference property. Since an assembly is classified as a manufactured element, it inherits all of the properties defined in Figure 26. The fully defined assembly block is shown below.

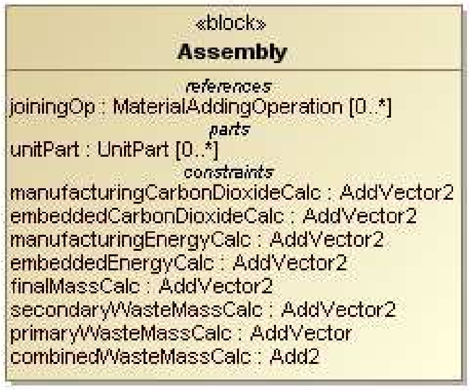

Figure 32: Assembly block

The structure of the assembly element is slightly different, but very similar to the structure of the unit part. The behavior for the block is also very similar to that of the unit part, but the PAR is slightly different to account for the assembly containing both ABC objects and activities. The assembly block contains similar constraints as the unit part block, but the actual relationships are slightly modified since the assembly only contains two part properties, rather than the three reference properties the unit part contains. The constraints can be seen in detail in Appendix A.2. Below is a visual representation of the parametric relationships in an assembly block. Notice the similarities with the unit part PAR diagram.

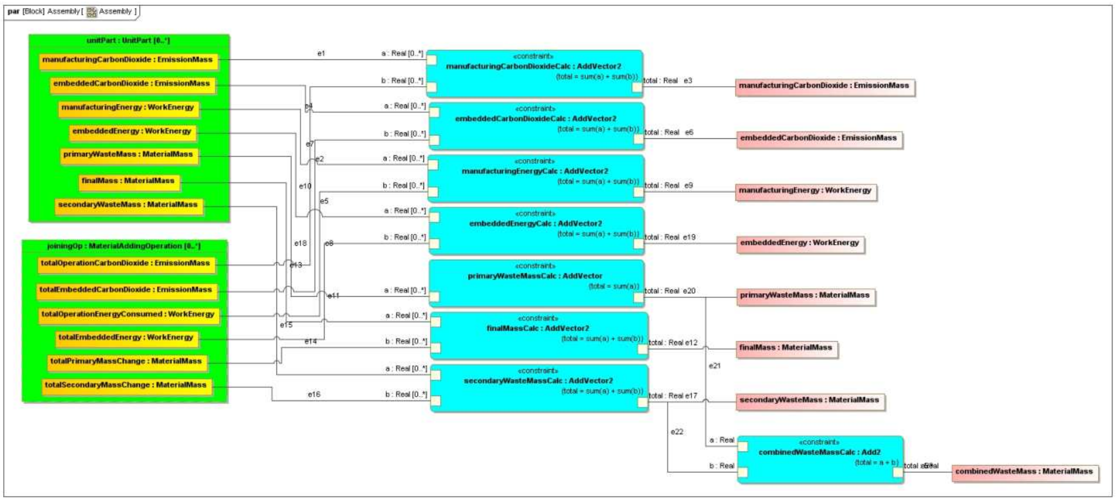

Figure 33: Assembly parametric diagram

The highest level block in the product level decomposition (in this thesis) is the product itself. The product contains assemblies, which in turn contain unit parts, which in turn are contain only manufacturing operations as part properties. This containment structure makes it such that the product's most fundamental component is a manufacturing operation. This upholds the ABC structure defined in Chapter 3. The definition of the product's block can be seen below. No value properties are shown since the block inherits all of its value properties from the manufactured element block defined earlier.

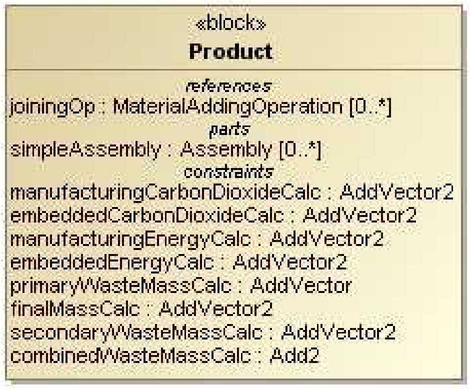

Figure 34: Product block

The product block is virtually identical to the assembly block definition, except that a product contains assemblies, while assemblies contain unit parts. The parametric structure is identical to that of the assembly block, except for the substitution of an assembly block for a unit part block. This can be done because much of the structure of the various manufactured elements is inherited from a common base classifier, leading to consistent and repeating structures inside the model.

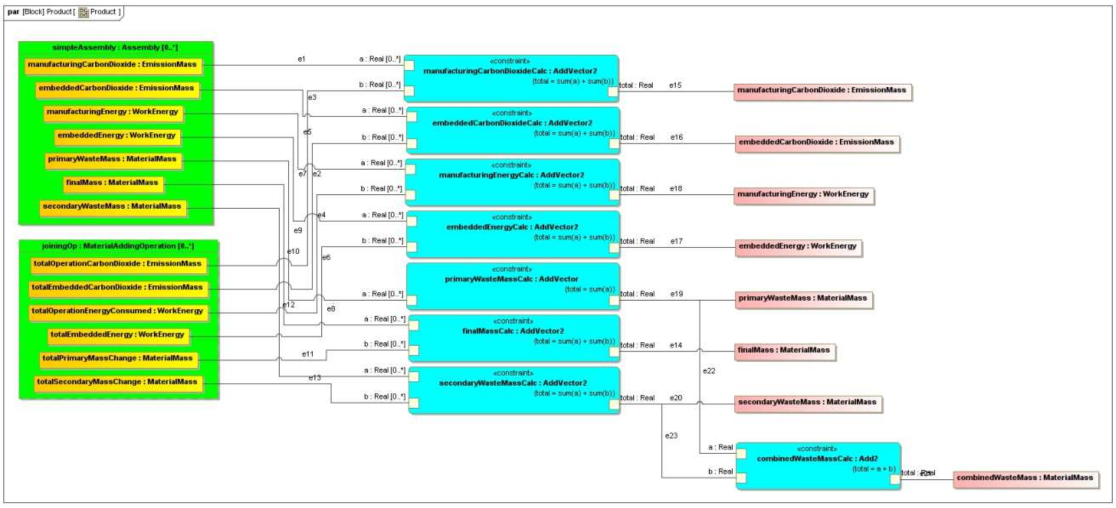

Figure 35: Product parametric diagram

This particular model only included three levels of the product element dimension. It is possible that a product can contain more than three levels of decomposition. Additional levels can be added to the model, each taking a form very similar to that of the assembly and product level blocks. So long as the new intermediate levels are classified as manufactured elements, they can fit into the parametric structure shown in Figure 33 and Figure 35. This improves the ABOOM Model's flexibility and reusability.

In adhering with the ABC structure defined in Chapter 3, the containment tree defined for a product level decomposition is such that the most fundamental element referenced by a product is the manufacturing operation. Intermediate levels, such as the unit part and assembly, add organizational structure, but they do not redefine the fundamental ABC principles on which the ABOOM Model is built.

4.7.2 Enterprise Element Objects

The operations in the activity space can be organized in another dimension, such as the enterprise perspective. This perspective groups activities by the manufacturing plant where they are performed. Within each plant, the activities can be further organized into processes. Outside of the plant, the entire system is organized in what is called an enterprise. This structure is fundamentally similar to that of the product element decomposition. Compare Figure 36 with Figure 28 to see the similarity.

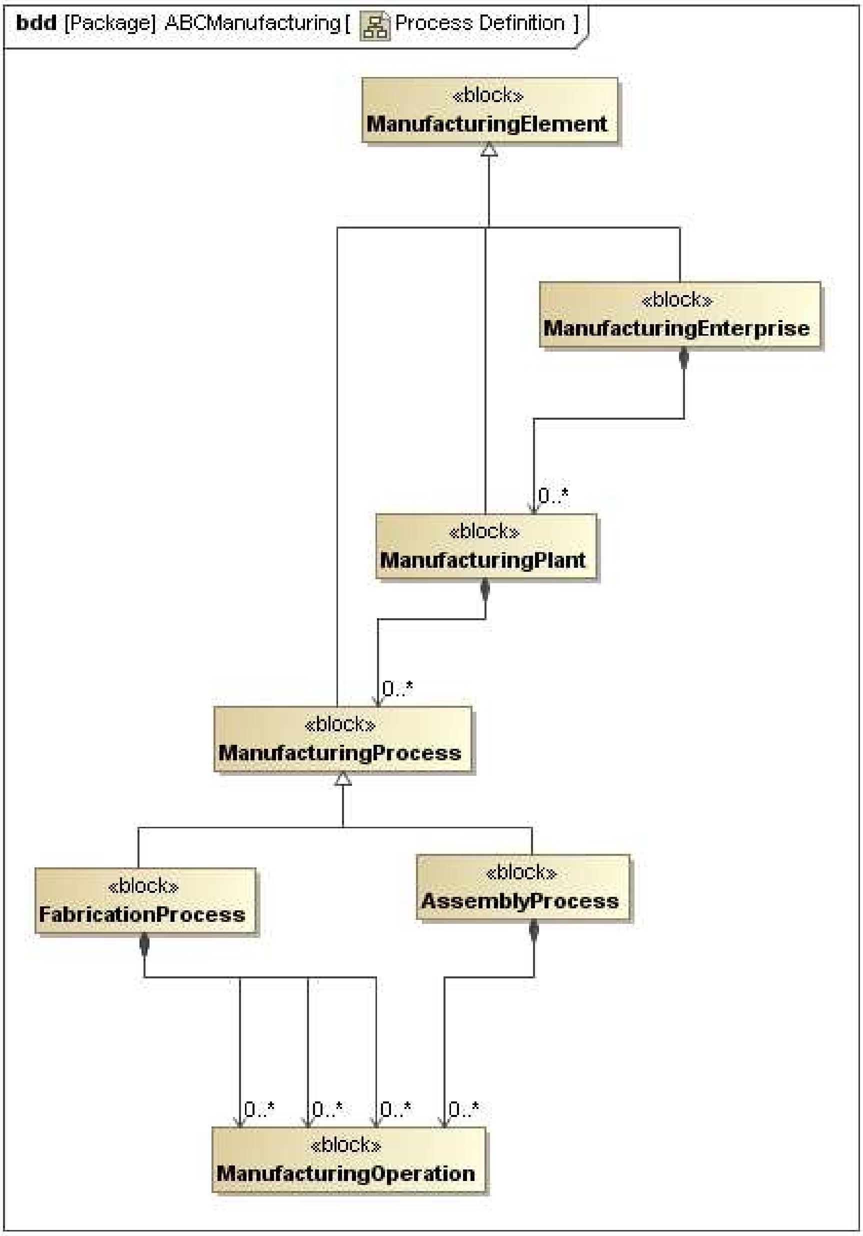

Figure 36: Hierarchy of elements from the enterprise perspective

The manufacturing process has been split into two parts, a fabrication process and assembly process. This is to add clarity as to what type of process is being undertaken. These two processes are generalized as a manufacturing process, which in turn is generalized as a manufacturing element. All of the elements in Figure 36 inherit the properties of the manufacturing element block, shown below.

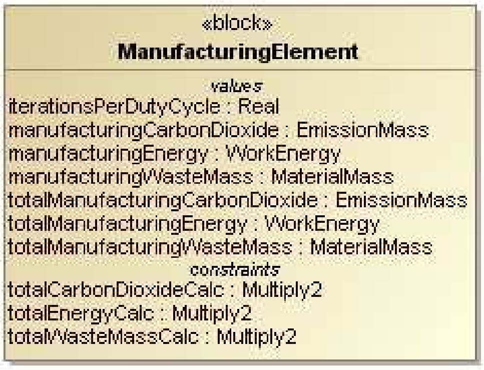

Figure 37: Manufacturing element block

The enterprise perspective requires that environmental burdens be quantified slightly differently than for a manufactured element. The primary difference is that a manufacturing element contains seven value properties (compared to the eight contained by a manufactured element) and these properties are slightly different. First, there are the values associated with the three burdens (energy, carbon dioxide, and waste) assessed for manufacturing alone. Embodied costs are assumed out of the scope for this particular perspective, as discussed in Section 4.3. The next value is the number of iterations per duty cycle, which is defined shortly. Finally, there are the total quantities associated with each of the three burdens over all iterations, just like *–perOp* burdens were totaled over all iterations for a manufacturing operation to get the total burdens. The PAR for determining the total costs from per-iteration costs is equally similar to that of a manufacturing operation from Figure 27. The PAR for a general manufacturing element is shown in Figure 38.

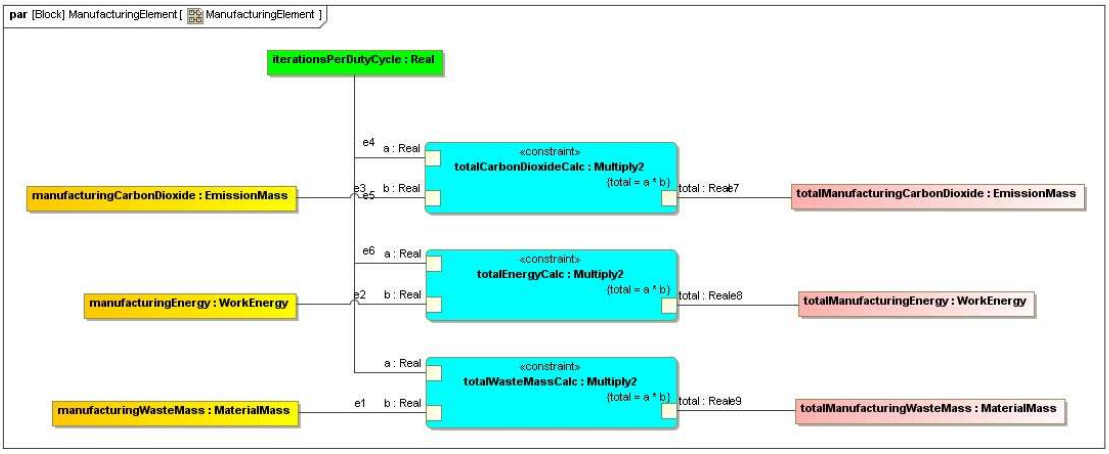

Figure 38: Manufacturing element parametric diagram

The value for *iterationsPerDutyCycle* is intended to represent how many times an enterprise performs a list of activities during some repeating length of time (duty cycle). A duty cycle can be a day, a week, a month, a year, etc. This is done so that an enterprise perspective analysis can provide manufacturing costs per year for a plant, for example, or similar analysis. Each manufacturing element contains the value for iterations per duty cycle, so there is a danger of over counting. The way this is handled in this thesis is on a day-week-year duty cycle system. This means that the lowest level manufacturing element, the process, the value *iterationsPerDutyCycle* represent the number of times that process is carried out in one day. For the next element, the plant, the value represents *the number of process duty cycles that occur in one week*. This is an important definition to keep in mind because the danger of double counting costs is with this definition. For a day-week-year system, a process' iterations per day represent the number of times that process occurs in a day, but for a plant, it represents the number of *days* that plant performs its processes in a week. In typical cases, this can be five iterations per week, representing a standard five business day week. Similarly, for the enterprise, the value indicates the number of *weeks* that the plants it contains operate in a year.

To further clarify this definition, an example is used. Assume a process occurs five times per day, the plant that contains the process operates six days a week, and the enterprise operates that plant for fifty weeks in the year. The *iterationsPerDutyCycle* for the process, plant, and enterprise would be five, six, and fifty, respectively. The danger of double counting occurs if the iterations used is anything other than similar to what was just described. In other words for the system just mentioned, a process occurs thirty times per week (five times per day, six days a week). This *does not* make the plant's iterations per duty cycle equal to thirty. If the plant's iterations was set to thirty, then it represents the process occurring 150 times per week (five times a day and an incorrect thirty iterations), rather than the actual thirty operations that occur during that week.

Other duty cycle definitions can be used also. A simpler day-year-year definition can be used, where the number of processes per day is defined, then the number of days in a year is defined for a plant, then the number of years in a year the enterprise operates that plant is defined. In the last case, the number of years in a year is unity. More complex systems can also be used.

Moving on, manufacturing processes are divided into two groups: fabrication and assembly. This is done to help add organization and clarity, but is not purely necessary. The manufacturing process block does not contain any properties or behaviors, but is merely used to indicate that fabrication processes and assembly processes both fill a process slot. The blocks for the two processes are shown below.

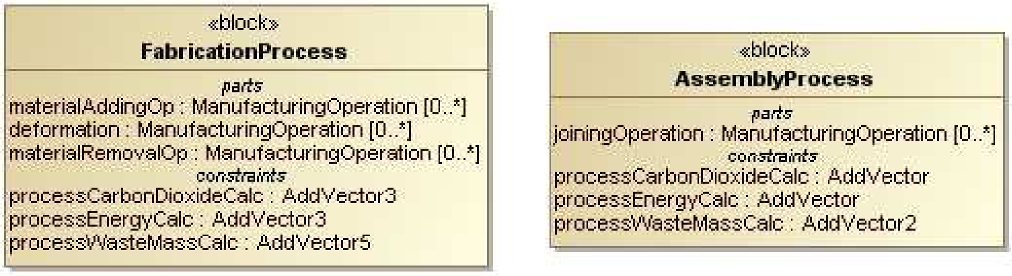

Figure 39: Fabrication and assembly process blocks

A fabrication process usually deals with creating unit parts, while assembly processes join parts together. They are distinguished from each other in that a fabrication process contain all three types of manufacturing operations (material adding, deformation, and material removal), while the assembly process only contain joining operations (a special case of a material adding operation). A manufacturing process inherits the value properties of a manufacturing element, and the fabrication and assembly processes inherit properties of a manufacturing process. Therefore, fabrication and assembly processes contain the value properties of a manufacturing element. The way in which these properties relate to each other can be seen in the PAR for the fabrication and assembly processes, show in the two figures below.

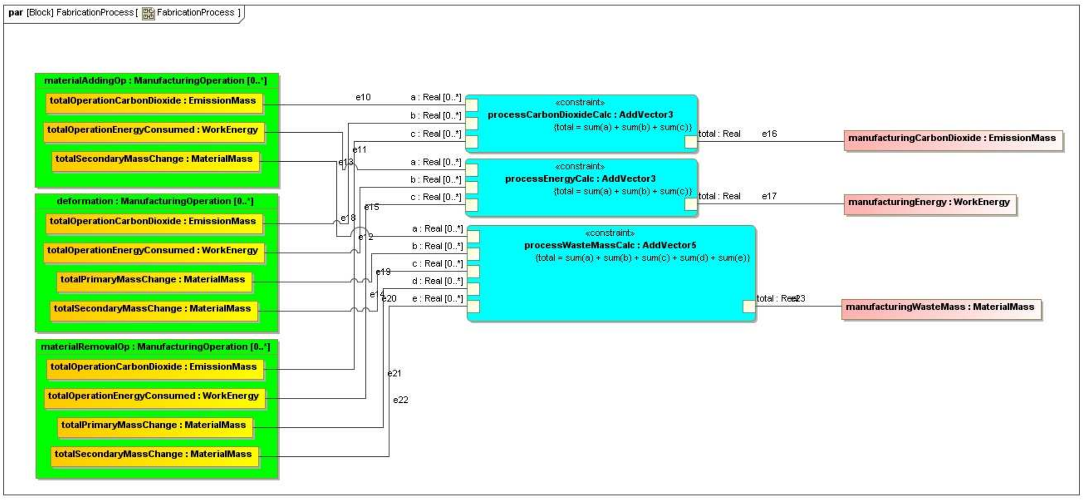

Figure 40: Fabrication process parametric diagram

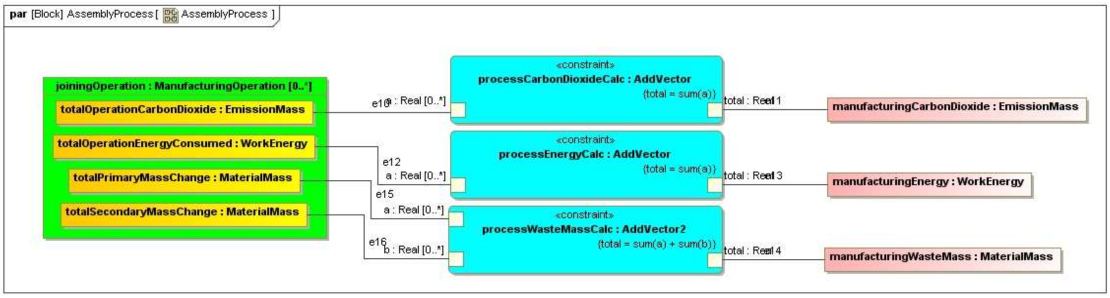

Figure 41: Assembly process parametric diagram

Processes are contained in a manufacturing plant. A plant can contain both types of processes, but is assumed not to contain any free-floating operations. Future versions of the model can be made to include facilities level, auxiliary operations. These auxiliary operations could include lighting, air handling, water use, etc., and would be contained by the manufacturing plant block. These operations are still activities, preserving the overall ABC structure from Chapter 3. The basic definition of a manufacturing plant, excluding auxiliary operations, is seen below.

Figure 42: Manufacturing plant block

The parametric diagram for the manufacturing plant is quite simple since there is only one contained element and only three constraints used to calculate costs. The costs are inherited from the manufacturing element block.

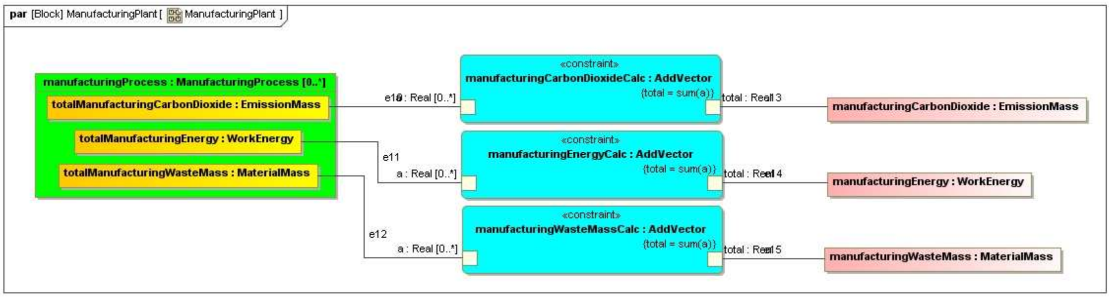

Figure 43: Manufacturing plant parametric diagram

Similar to the manufacturing plant, the enterprise level block is quite simple, containing only one type of element. The parametric diagram for the enterprise level is equally simple. As with the plant block, future addition of auxiliary operations on an enterprise level can be added to the enterprise block, so long as they fit the ABC structure.

Figure 44: Manufacturing enterprise block

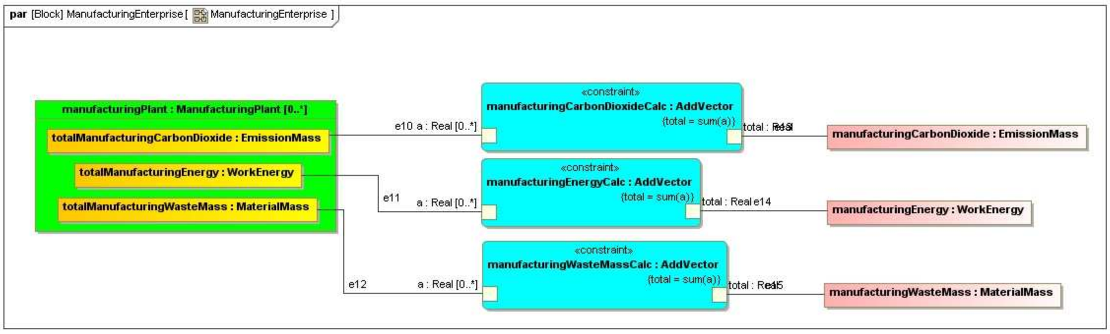

Figure 45: Manufacturing enterprise parametric diagram

4.8 Pre-Determined Inventories and Libraries

The structure of the model is fully defined. In order to create a scenario, instances of various model elements must be created. Of the instances that are created, many of them can be common to multiple scenarios. These instances represent resources whose properties do not change from one scenario to the next. Reusable instances are stored in pre-defined libraries that are available prior to building a specific scenario. The reusable instances and their values can be determined from pre-existing LCI's and databases. In some cases, resources are common to all scenarios, while in others the resources are common only to a few scenarios. In any event, the user is free to define additional instances in the resources libraries.

4.8.1 Fuel Library

Fuel resources can be common across many scenarios. There are two lists of fuel resources that can be utilized by a variety of specific scenarios. The first list is of general fuel resources, while the second is of electricity sources. Each list is idealized and can be used in the generation of a near-theoretical scenario.

The list of general fuel resources can be seen in Appendix A.3. (Energy Information Administration, 2009) (World Coal Institute, 2009) When it is said that the fuel resources are idealized, it is assumed that there are no embodied costs associated with the fuel resource. The only cost associated with the fuel resource being consumed is the *specificCarbonDioxide* property from Figure 21. This helps establish a theoretical baseline minimum for the costs of performing an operation.

The second list of fuel resources that was created prior to scenario modeling is the electric resource library, shown in full in Appendix A.4. (Energy Information Administration, 2009) This library represents electrical grids in the United States of America, broken down by state and region. Like the previous library of fuel resources, these resources are idealized, meaning there is no embodied cost associated with the resource. It can be said that the carbon dioxide emissions per joule are actually emitted by the power plant and not by the actual operation, but here it is assumed that the emissions took place as a direct result of consuming a quantity of electrical resources, and thus appears under the value property *specificCarbonDioxide*.

Each of the entries in the lists was instantiated in the SysML model. Additional fuel resources can be added as needed.

4.8.2 Material Library

Material resources can be common to multiple scenarios. Many properties of the material (if not all of them) would not change depending on the scenario. Just like with the fuel resources, material resources information can be extracted from existing LCI's and databases. No distinct library of material resources is defined here. A small library of material resources is defined in the later section on constructing a case study.

4.8.3 Machine Library

A library of machine resources can be constructed ahead of time. Machines used to perform operations can vary much more from scenario to scenario than a fuel resource, but generally there is a fixed, limited list of machines available to perform a manufacturing operation. A user can survey available machines prior to the construction of a scenario. For each available machine, an instance can be created, forming a library of machines the user can choose from.

If a survey of machines is not possible, or too difficult, an ideal machine can be used. The instance block for an ideal machine can be seen below.

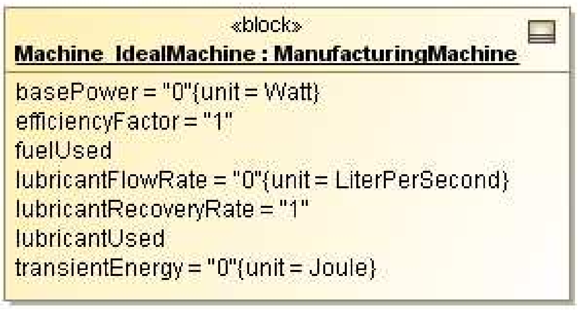

Figure 46: Ideal machine instance block

An ideal machine has no base power consumption and no transient energy spikes. This means that the operation energy cost will consist of only the theoretical energy to perform the operation. The efficiency factor is equal to 100% and 100% of the lubricant is recovered. This means that no energy is lost to an inefficient machine, and the lubricant choice does not matter, since all of it is recovered and none contributes to embodied costs or waste mass. However, the lubricant flow rate is 0 L/s, meaning that regardless of what lubricant is chosen, none is consumed. Using an ideal machine means that the costs associated with an operation are as close to theoretical as possible.

4.8.4 Fastener Library

A library of available fasteners can be defined ahead of time. A specific list is not defined here, but is rather defined during the construction of an LCI for the case study. Information about a fastener can be determined from existing sources. Tables of fastener properties have already been defined, so a user merely needs to enter values from these tables into instances of these fasteners.(Shigley & Mischke, 1989) Otherwise, a user can survey available fasteners manually, just like with the machine resource library.

4.9 Validation and Model Verification

4.9.1 First Criterion

The first criterion states that the model should not violate any fundamental laws of physics, without proper assumptions. Two fundamental laws that must be upheld are conservation of mass and conservation of energy. Both are conserved in the ABOOM Model.

The model conserves mass by increasing a product's mass after a material adding operation, and removing mass after a material removal operation. Furthermore, the mass assigned to the primary waste mass goes up after a material removal operation. A simple mass conservation can be seen in the following example.

The example specifies a unit part that is made of aluminum. It undergoes the two types of manufacturing operations (material adding and material removal), but no deformation since deformation does not change part mass. The part is a meter cubed block that has a 0.1 m^3 hole drilled into it. It is assumed to use an ideal machine powered by Georgia grid electricity during all operations. The definition in SysML of the sample part and its sample operations is given below.

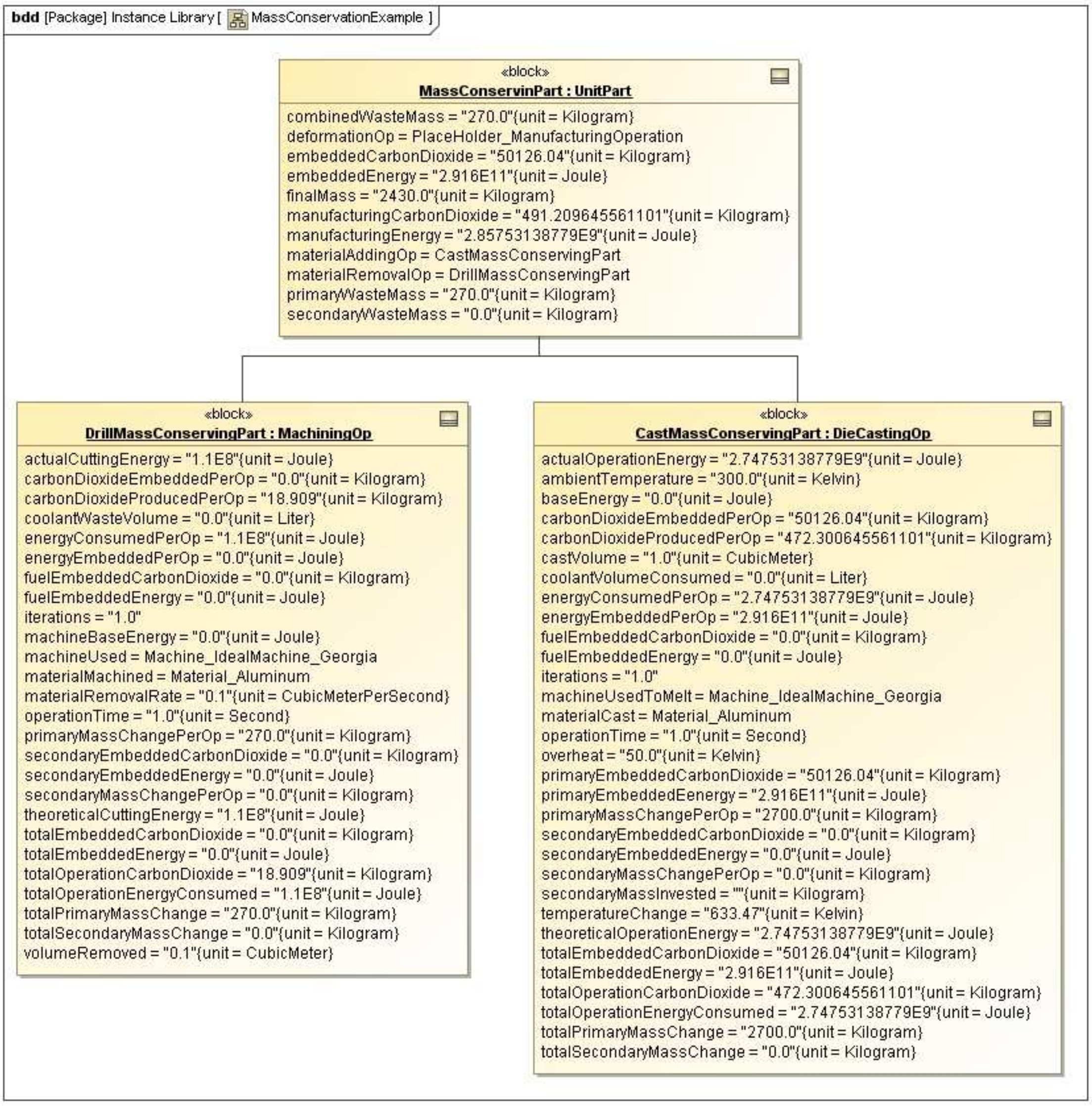

Figure 47: Mass conserving system example

It can be seen that the material adding operation adds 2700 kg of aluminum to the part's mass, while the material removal operation removes 270 kg. The part's final mass should be 2430 kg, which is indeed the case with the example part. However, the total system primary mass must still be 2700 kg, since that quantity was added by the operation. The 270 kg that were removed from the part now appear as primary waste mass, making the system's total mass conserved. Mass is similarly conserved with secondary materials, though not explicitly shown here.

Mass is conserved for carbon dioxide as well. It is indicated that 18.909 kg of carbon dioxide is produced during the machining operation, while 472.300 kg are produced during die casting. The part's manufacturing carbon dioxide should be 491.209 kg, which is the case as shown in the unit part's block. Embodied carbon dioxide is calculated in a similar way, and it also conserved.

Energy is also conserved in the ABOOM Model. Embodied energy is calculated similarly to embodied carbon dioxide, so it is conserved in the same way carbon dioxide is conserved. Manufacturing energy is computed for each operation using first order equations well documented in literature. (Kalpakjian & Schmid, 2001)(Kalpakjian & Schmid, 2003)(Tlusty, 2000)(DeGarmo, Black, & Kohser, 1997) No fundamental laws are violated in these equations.

Overall, it is assumed that no physical laws are violated by the ABOOM Model.

4.9.2 Second Criterion

The second criterion states that the model should make decision making between design points non-trivial. The model's user can chose between processes and resources, and these decisions must produce distinguishable results. Choosing amongst the processes will yield unique results in this model. All ten of the manufacturing activities are fundamentally unique. Even similar operations, like sand casting and die casting or cold and hot extrusion, require different input values and use different properties of the material to calculate costs.

All resources are made highly unique by their embodied costs. Even two identical materials can have different costs if harvested and refined differently. For instance, virgin aluminum is identical to recycled aluminum, except that the embodied costs of virgin aluminum are much higher than those of recycled aluminum.

Material resources are made more unique by their physical properties. For instance, the cutting energy of titanium is higher than the cutting energy of aluminum, therefore, the machining costs of titanium are higher than the machining costs of aluminum. This is true not only for solid material resources, but liquid material resources also.

Fuel resources are made more unique by their physical properties as well. In particular, fuel resources have a value for specific carbon dioxide emissions per unit energy produced. This value varies from fuel to fuel. It is possible, though extremely unlikely that the specific carbon dioxide emissions rate is identical for two different fuels. Nevertheless, these two fuels will likely vary on embodied costs, making them unique.

Overall, it is possible for two different processes or two different resources to have identical costs, but this is most extremely unlikely. If a user chooses two different processes or two different resources, the costs will change accordingly.

4.9.3 Third Criterion

The third criterion states that the predicted cost for an operation must be within an acceptable error margin from actual, empirically gathered results for an operation. The definition of an acceptable error margin can vary, depending on the user. It is common practice in mathematics to consider a 5% error or less statistically insignificant. (Wikipedia, 2010) For the purpose of this thesis, an error less than 10% is assumed to be acceptable, while less than 5% is assumed perfectly accurate. The 10% threshold is arbitrarily chosen as twice the conventional value for statistical significance.

4.9.3.1 Experiment Introduction

At this time, it is impossible to validate the third criterion for all parts of the model. Instead, an experiment is performed to verify part of the model. This experiment can be repeated for other parts of the model to validate the model as a whole. Specifically, this experiment gathers data on the amount of energy consumed by a machine to perform a material removing machining operation. The amount of energy consumed during the machining operation is compared to the SysML predictions and error is calculated.

4.9.3.2 Experiment Objective

The main objective is to gather actual machining energy data for a sample part and compare the actual energy to the SysML model predicted energy. The percent error is calculated to determine whether the model acceptably predicts the energy consumed during the operation.

4.9.3.3 Experimental Setup

The part being machined is a slab of 6061-T6 aluminum. The slab has a square channel machined into one side and four identical holes machined into the other side. The 3D CAD image of the part is shown below.

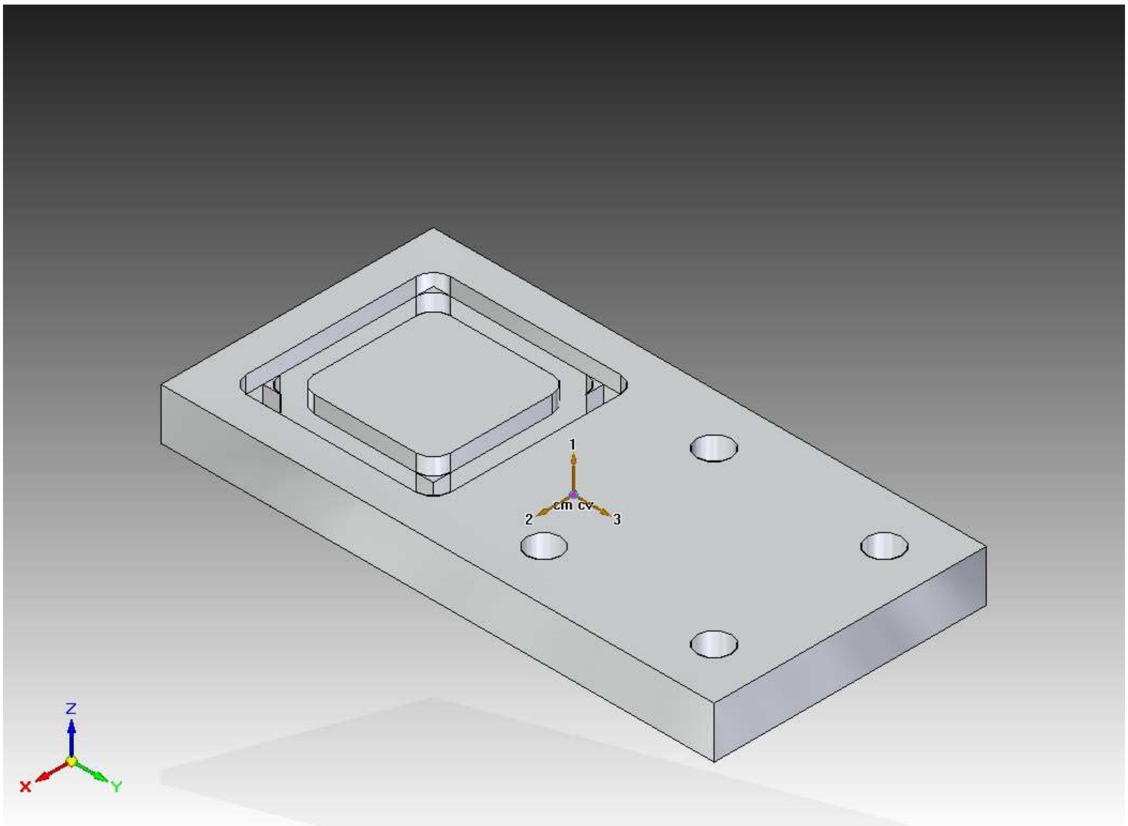

Figure 48: Validation experiment test part

The overall part is 8.25” long, 4” wide, and 0.75” thick. The holes are 0.5” in diameter. The channel is 0.25” deep, 3” square from the outer edge, and 0.5” wide. Full multiview drafts can be seen in Appendix C.1.

The machine used to produce the features on the part is an Okuma MILLAC-44V computer numerical control machine tool. Figure 49 shows the machine tool.

Figure 49: Okuma MILLAC-44V machine tool

The Okuma has an 11 kW spindle motor and uses an external power transformer to provide the Okuma power. The complete specifications of the tool are given below.

Table 1: Experimental machine characteristics

Name	Okuma MILLAC-4V
Supply Voltage	220/480 V
Phase	3 Phase
Frequency	60 Hz
Rated Capacity	26.9 kVA
Largest MOT Rate	80 A
Interrup Cap	25/7.5 kA
Diagram #	DR40146
Serial #	673411

A two flute, 0.250” end mill was used to cut out the channel, while a two flute, 0.500” drill was used to produce the holes. The spindle was running at 2500 RPM at a feed rate of 8” per minute during the entire operation. The drilling was a peck drilling operation where the bit was thrust in-out-in-out many times to foster chip formation. Each thrust was approximately 0.1”.

The instrument used to measure the power consumed by the Okuma was a Fluke 43b Power Quality Analyzer. The Fluke is capable of measuring 3-phase power up to 400 A and 1000 V. The Fluke was attached to the Okuma’s power supply after it passed through the transformer. An IBM Think Pad laptop was used to log data from the Fluke during the experiment.

4.9.3.4 Experimental Procedure

The procedure for the experiment is described below.

1) The entire machine was disconnected, along with power to the transformer
2) The Fluke was connected to the machine’s incoming power supply, after the transformer
3) The Fluke was connected to the laptop and all connections were checked
4) The transformer is connected to power
5) Data logging began on the laptop using the Fluke
6) The Okuma was connected to power and was left to idle for a few moments
7) Panel lights and Okuma control panel were turned on
8) Appropriate bits were inserted into the Okuma
9) The Okuma spindle was warmed up at 500 rpm for about 20 minutes
10) The blank work piece was mounted in the Okuma
11) The spindle position was zeroed relative to the work piece
12) The coolant pump was turned on
13) A few seconds after the pump started, machining began
14) The channel was milled in six passes
15) The holes were “peck-drilled” one at a time with a plunge depth of about 0.1”
16) The spindle repositioned itself and machining stopped and the pump was stopped
17) The Okuma was left on while data logging was stopped

4.9.3.5 Experimental Results

The Fluke logged the power consumption of the machine once per second. The complete results are plotted and displayed below.

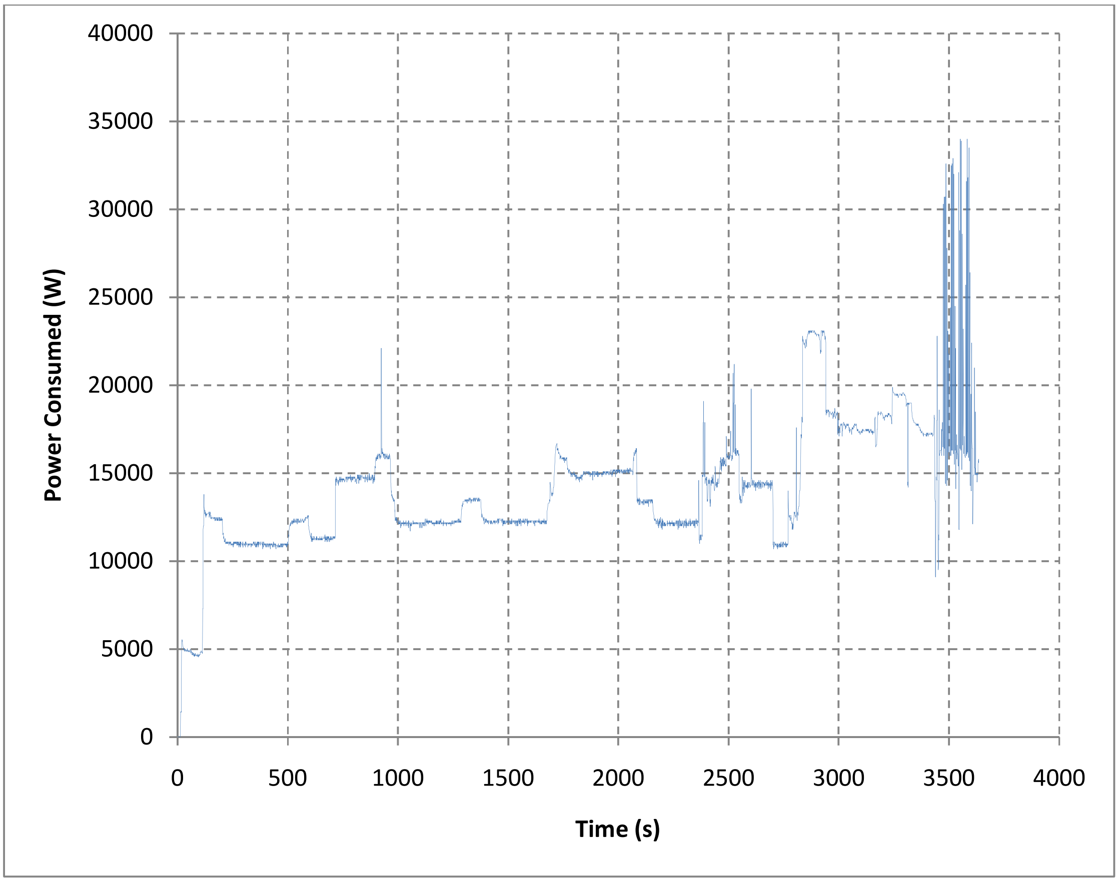

Figure 50: Machining operation logged data

Actual machining did not begin until about 2750 s (46 min) into data gathering. Figure 51shows the actual machining in more detail.

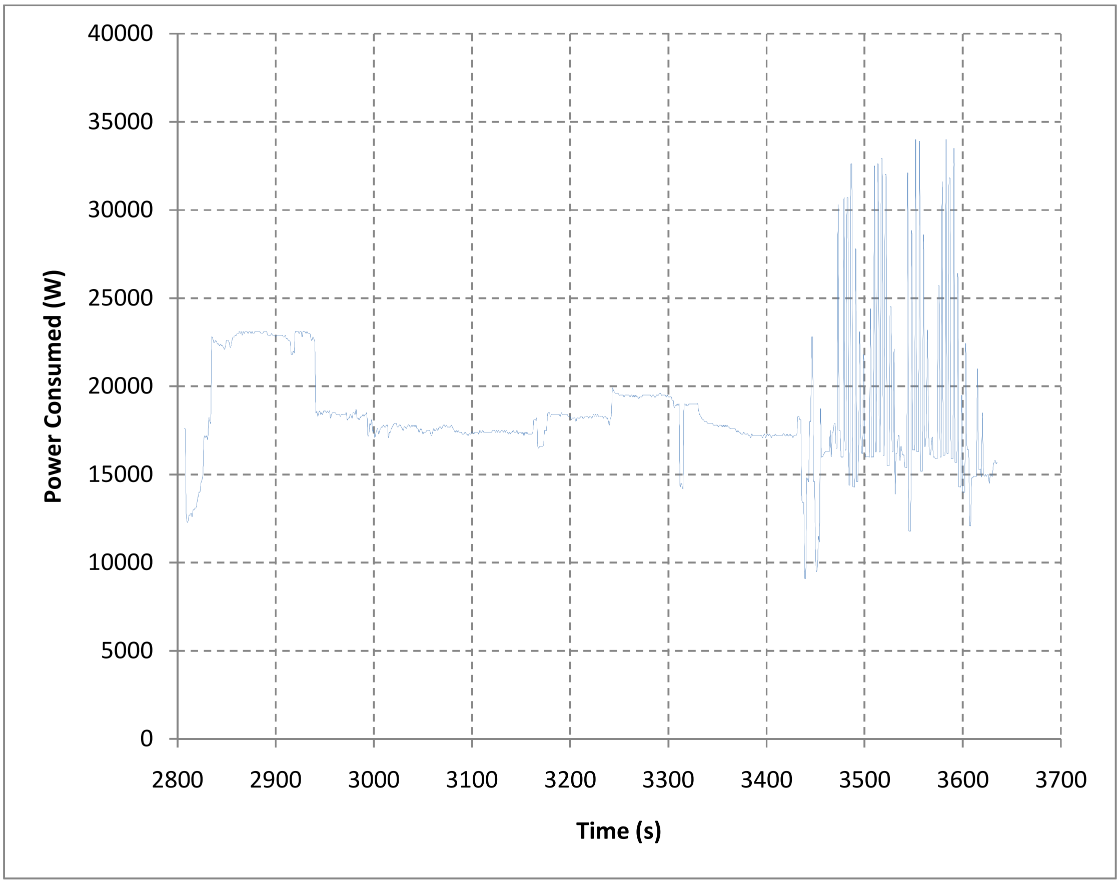

Figure 51: Close up of machining operation results

The following figure shows visually shows approximately when events happened, with each event numbered. A list of events and their time stamp is given below for reference.

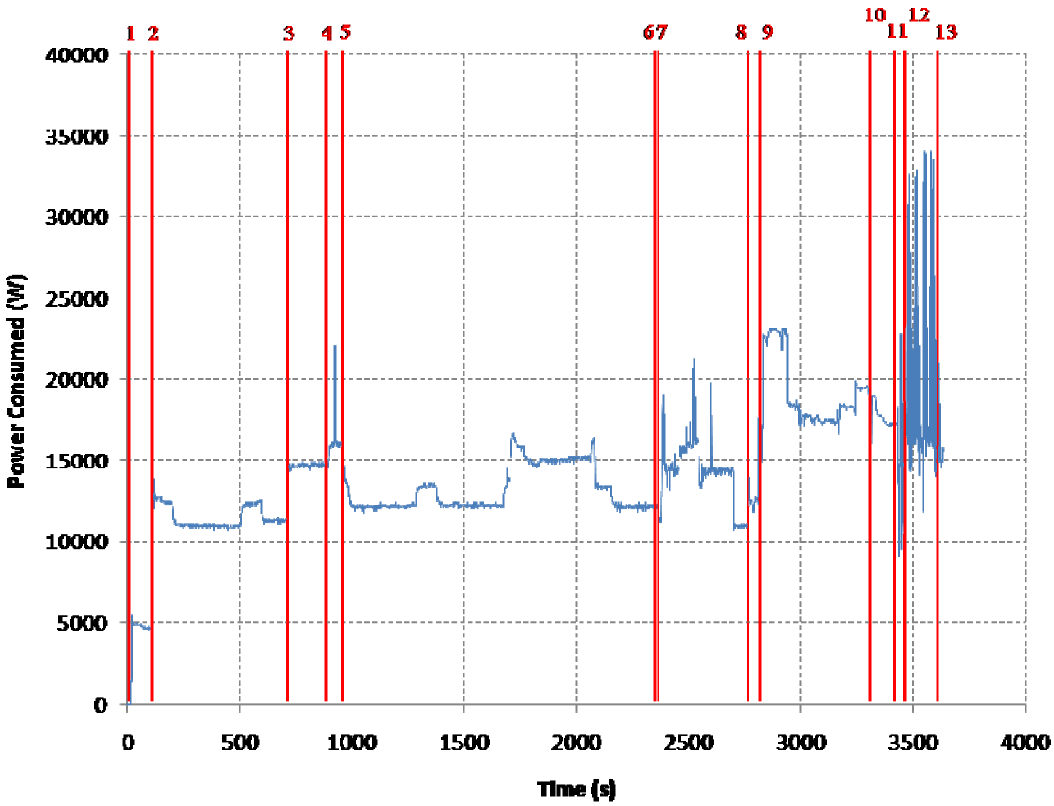

Figure 52: Experimental results with events indicated

Table 2: Time of events during experiment

Index	Time (s)	Event
(none)	0	Data gathering begins
1	13	Machine turned on
2	116	Control panel turned on
3	717	Tool bits inserted
4	924	Tool bits changed
5	986	Spindle warm up begins @ 500 rpm
6	2365	Spindle warm up stops
7	2370	Positioning of blank begins
8	2807	Pump turned on
9	2834	Milling begins
10	3312	Pump Momentarily Turned Off
11	3440	Milling ends and tool bit change
12	3457	Drilling of holes begins

Table 2 continued

Index	Time (s)	Event
13	3621	Drilling ends
(none)	3635	Data gathering ends

4.9.3.6 Experimental Analysis

From the experiment, it can be concluded that the machine's base power is approximately 18.6 kW. This is made up of several parts. First, idling the machine with no systems on consumed about 5 kW. Turning on the control panel and all internal systems consumed an additional 6 kW. Internal systems include running lights, active sensors, and power conversion and monitoring. Idling the spindle consumed about 1 kW. Running the lubricant pump consumed about 5 kW. A total base power of 18.6 kW is rather high, but the Okuma is an advanced machine with many internal operating systems, designed to machine precision features into very large parts. The Okuma is approximately five times more powerful than the machine tool used for the Lodhia and Drake experiment. Several transients were identified that correspond to inrush power for turning on various motors, etc., and also for changing bits. However, there were some unidentified transients. It is not clear at this time as to what caused these transients, but a few educated guesses can be posited. The machine included many motors (axis control, pump, spindle) so some large transients could have been motors adjusting position or responding to fluctuations ("biting" into a fresh section with the cutting but, or the pump compensating for a surge in fluid levels). Furthermore, a number of sensors on the Okuma keep track of the spindle position and speed, as well as fluid levels, feed rates, and so forth. Transients could have been caused by the Okuma performing periodic status checks to ensure proper cutting. Lastly, transients occurring near the beginning and end of different operations that require motor control could be the inrush current required to initially start a motor from rest.

Milling took about 631 s (10:31 min), while each drilling action took about 45 s.

The breakdown of power consumption can be seen graphically in Figure 53.

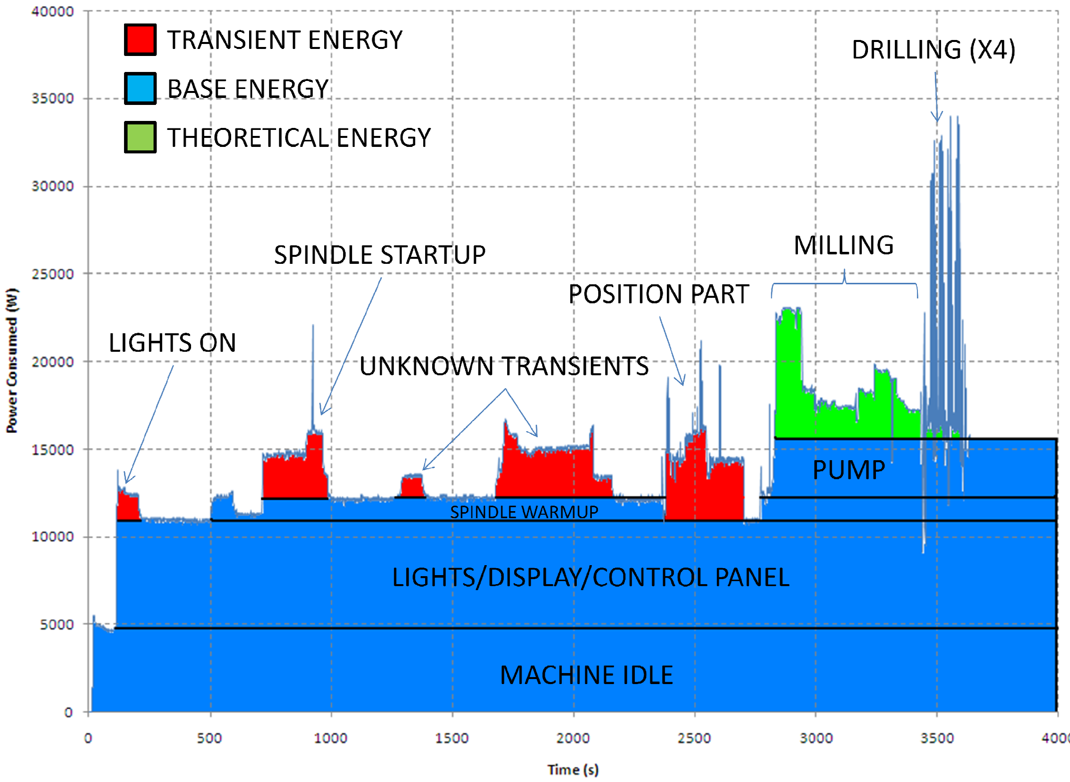

Figure 53: Breakdown of power consumption by activity

For the overall experiment, the total energy consumed is about 51.14 MJ of electrical energy. This is mostly due to the high base energy cost of the Okuma. The total energy consumed during milling (including base energy) is about 11.78 MJ, while the four drilling operations combined consumed about 3.34 MJ of energy.

The theoretical energy for the milling operation can be calculated by subtracting the base energy from the total milling energy. Since the base power was about 17 kW, and the milling operation lasted 631 s, the approximate theoretical energy for the milling operation is approximately 1.05 MJ. Similarly, the combined theoretical energy for the drilling operations is approximately 2.57 MJ. These values are compared in Section 4.9.3.8 to the predicted SysML results.

4.9.3.7 SysML Model and Predictions

The purpose of the ABOOM Model in this experiment is to predict the amount of energy that is consumed while machining features into a part, without having to resort to direct measurements. The purpose of the experiment is twofold. First, the experiment establishes baseline machine properties, like base power consumption. Once baseline properties are established, they do not need to be re-measured with every iteration of the model or experiment. Secondly, the experiment compares theoretical values to real-world values to determine a relative error associated with using first order principles.

The instance model of the experimental scenario needs to be constructed in the ABOOM Model. This begins with an inventory of the resources used in the experiment. Next comes the definition of operations performed in the experiment as well as the definition of the unit part itself. Finally, the ABOOM Model uses ParaMagic to come up with a prediction.

First, a machine inventory was created. It was assumed that the Okuma had a base power of 18.6 kW and used a generic lubricant. The lubricant type and lubricant flow rate are not critical since the Okuma recovers 100% of consumed lubricants. Transients were neglected as a simplifying assumption. The Okuma ran on Georgia grid electricity. The instance for the Okuma machine can be seen below.

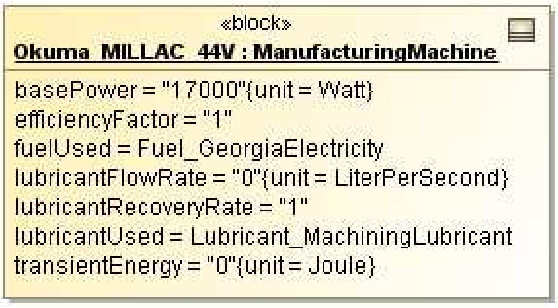

Figure 54: Okuma machine instance block

Next, the material resource for the part was created. The instance block for 6061-T6 Aluminum can be seen below.

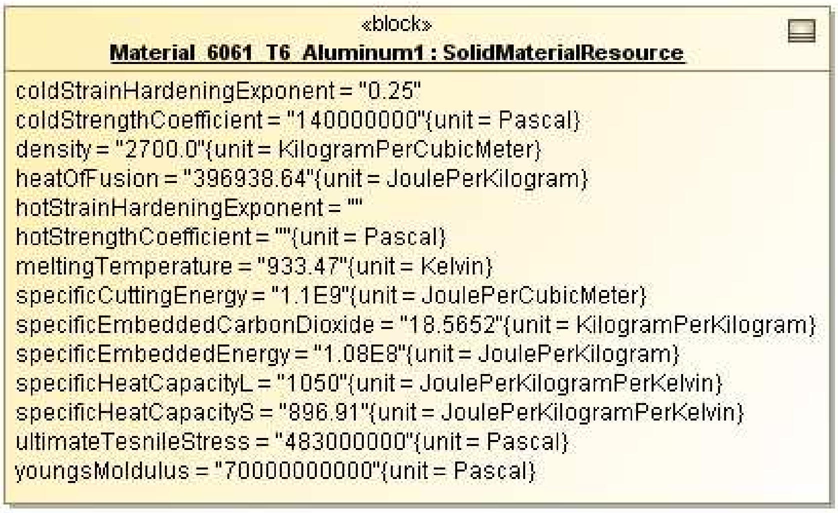

Figure 55: Aluminum material resource instance

Next, the two operation instances were created. The input values for operation duration is based on the experimental data. The rest of the data comes from the part's CAD file. As of when this experimental instance model was created, data extraction from the CAD file into the ABOOM Model was done manually. In the future, it may be possible to automate this step.

Figure 56: Experiment operation instance blocks

Finally, the two operations were assigned to a unit part instance representing the experimental test part. Though a material adding operation did not occur at the time of this experiment, the blank work piece was a piece of extruded aluminum. Since machining is being validated at this time, and not extrusion, a placeholder material adding operation is added to indicated primary mass was added to the system, but no costs are associated with that operation. Since there was no deformation operation, a placeholder operation was also used for the deformation operation slot. Placeholder operations fill in slots that need to be filled, but they do not add costs or information to the model that would change results. The slots need to be filled with an instance, even if there is no operation to fill that slot. That is why placeholder operations are used.

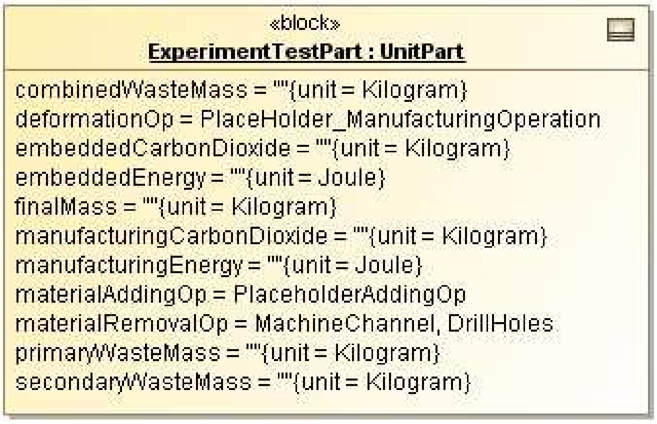

Figure 57: Experiment test part instance block

The model was simulated using ParaMagic and estimates as to the amount of energy required to perform the two operations were returned. According to the SysML model, about 10.75 MJ of energy are consumed by the milling operation, of which 22,290 J are from actually milling. For the drilling operation, 3.03 MJ of energy were consumed to drill the four holes, of which about 10,620 J came from actual drilling.

4.9.3.8 Comparison of SysML Predictions to Experimental Results

The SysML model predicted 10.75 MJ would be consumed by the milling operation, when actually 11.78 MJ were consumed. This is an error of about 8.7%. The

SysML model predicted 3.03 MJ would be consumed drilling, while 3.34 MJ were actually consumed. This is an error of about 9.3%. Overall, the ABOOM Model was within close and acceptable error with predicted results.

It becomes evident that the energy consumption is dependant heavily on a reasonable assumption of machine base power consumption. The value of 18.6 kW as the Okuma's base power consumption is an estimate based on measurements taken my the Fluke. To give an idea of how much of a difference just 0.1 kW difference in base power estimation can produce, machining the channel took 631 s, leading to a decrease in predicted energy consumption during that operation of 63.1 kJ. This would make the predicted milling energy consumption 10.687 MJ. An error of just 0.5% in the base power consumption leads to an overall prediction error of 3.7%. This means that an accurate estimation of a machine's base power consumption must be made. It is possible to get 100 W resolution (and much fine) with an instrument like the Fluke, so it is not unreasonable to expect the machine's base power be estimated within sufficient accuracy.

4.9.3.9 Conclusions About Third Criterion Validation Experiment

Though there was some error in predicting the base energy of the machine, the SysML model was able to predict machining energy costs to less than 10%, constituting close and acceptable error. Despite the large error in the theoretical energy cost, the overall cost was not affected greatly since the actual machining consumed a relatively small part of the overall machine's energy consumption. Much more energy was consumed running motors, pumps, lights, control systems, etc. that was spent on actual machining.

Given the results from the experiment and the comparison with the SysML model predictions, it is concluded that the SysML model did predict actual machining costs to within an acceptable margin of error for a machining operation. Therefore, it can be assumed that for a machining operation the third criterion is upheld, just barely. However, it should be noted well that the accuracy of the SysML model's prediction for a machining operation rely heavily on the quality of the estimated machine base power consumption.

The Third Criterion could only be validated for this time for energy consumption of a machining operation. This leaves part of the machining operation and nine other complete operations with uncertain validity. A similar experiment to what was performed here can be repeated for the energy consumption of the nine other operations. Similarly, an similar experiment that measures carbon dioxide emissions can be performed for the ten experiments to further validate the model. Since all of the nine untested operations were modeled using similar first order principles as the machining operation, it is assumed that the results from their validation experiment will be similar to the results from the machining experiment. Based on the experiment performed, at this time the Third Criterion is considered satisfied.

4.10 Creating a Federated Model in SysML

As mentioned in Chapter 3, Section 3.7, the federated model for the manufacturing system can contain a manufacturing bill of materials, a chronological process plan, and a description of the flow of materials through the system. Other areas can be included in the federated model but are not mentioned in this thesis.

The ABOOM Model already includes information for a manufacturing bill of materials. The product level decomposition of a manufactured product decomposes high level manufactured elements into lower level manufactured elements. Through the use of containment and reference properties and BDD's and IBD's, the information generally found in a bill of materials is represented in the ABOOM Model. Next, representing a chronological order of operations, seen with the Sequence Index dimension in the Activity Space, for a process plan can be done through the use of an Activity Diagram (ACT). These diagrams resemble Petri Nets in that the path "tokens" take is traced through a system of actions and nodes to indicate an order of activities. Activity diagrams can represent manufacturing operations as *actions* that are ordered and joined together in a flow diagram. Lastly, physical flow of materials through the manufacturing system can be represented with the use of Internal Block Diagrams (IBD). These diagrams, as the name suggests, look at what is going on inside of a block. Internal block diagrams show many similarities to PAR's, but rather than showing the connection of value properties amongst elements in a block, an IBD shows the physical flow of elements amongst part or reference properties of a block. These flows enter and leave parts of the block via ports, which indicate what can flow through the port and the direction. Lines connecting flow ports can also represent what is actually flowing amongst ports and the direction.

The use of BDD's, ACT's, and IBD's are by no means the only way of defining elements in a federated model in SysML. The use of Sequence Diagrams can also be included to show a more detailed process plan as well as the flow of information amongst manufacturing elements. Use Case diagrams can also support logistical definition by indicating how many workers are needed to perform a particular operation. Though it is possible to define additional elements in the federated model, it is not the focus of the thesis to detail all the possible ways to model the manufacturing system in SysML. Therefore, for the two case studies defined in Chapter 5, only ACT's and IBD's are used in addition to the original ABOOM Model's BDD's and PAR's to define process plan and logistical flow of materials.

4.11 Conclusions About the SysML Model

The three criteria of a valid SysML model were tested. The First Criterion says that no physical laws are violated by the SysML model, and this is seen to be the case with an inspection of the mathematical models used. The Second Criterion says that for the SysML model to be valid, it must make decisions non-trivial. This is the case with selecting between processes, operations, material resources, and fuel resources, whose properties make each fundamentally unique. The Third Criterion states that the numerical results from the SysML model must be reasonably close to actual results. This was tested with an experiment for one part of the model. Due to resource constraints, full validation of the Third Criterion could not occur. Nevertheless, based on the results of the experiment, it is likely that the Third Criterion would be upheld for other parts of the model. Overall, the SysML model is assumed to be validated based on the three tested criteria.

With respect to the two research questions, it is shown that SysML is capable of creating an ABC model of a manufacturing system while providing meaningful, scenario-based results. The following chapter goes through a case study for a hypothetical wing structure to further demonstrate how the SysML model answers the two research questions.

5 Case Study: Hypothetical Wing Structure

5.1 Chapter Overview

This chapter demonstrates how a scenario model can be constructed in the ABOOM Model, as well as show what a scenario model looks like and how it is solved. The chapter describes how the ABOOM Model is used in a comparison of two hypothetical, notional wing structures. The chapter begins with describing the hypothetical scenario before describing the actual products being modeled. In Sections 5.4 – 5.6, the chapter describes the actual construction of the scenario models in the SysML ABOOM Model. Section 5.7 compares results from the two different scenarios. The chapter ends with Section 5.8, which draws conclusions about the ABOOM Model and discusses how it ties back to the original three research questions from Chapter 1, Section 1.7. In particular, this chapter looks at whether the ABOOM Model can return meaningful results and the general usability of the ABOOM Model (second and third research questions).

It is important to note that at the time of this study, the ABOOM Model used all containment properties, instead of both containment and reference properties. This was due to the limitations of ParaMagic at the time. The correct use of elements according to SysML is as has been described earlier in the thesis. Replacing reference properties with part properties in this study only serves analytic purposes at the time of analysis.

5.2 Scenario Description

A designer is trying to decide between two alternatives for a wing segment on a small unmanned aerial vehicle (UAV). Both designs have been modeled in CAD software, and both are equally acceptable choices. The designer wishes to choose the design that minimizes environmental impacts during manufacturing. Once a design is chosen, the designer needs to determine the environmental impacts of having the part produced in two different plants. One plant does only fabrication processes, the other does some fabrication and all assembly processes. The first plant is located in the state of Georgia in the United States, while the assembly plant is in Missouri. Transportation between plants is omitted here.

5.3 Product Definition

The product is a wing segment for a small UAV. The length of the segment is 0.75 m, with a cord length of about 0.41 m. The aerofoil is symmetric about the chord line. The entire construction is made of aluminum joined by fasteners.

There are two alternatives. The first alternative is a wing made with primarily sheet metal components. The second alternative is made of cast and machined components. The sheet metal wing requires more parts to be manufactured, but the cast wing has larger and thicker components that are stronger. The cast wing allows more space between ribs that can be utilized with additional equiptment, but the sheet metal wing is lighter. The designer has determined that both wings will perform equally well, but wishes to choose the product with the smaller environmental impact during manufacturing.

5.3.1 Cast Wing Description

The cast wing is composed of one spar and five ribs. Each rib is split into a nose section and a tail section, making a total of eleven parts, of which there are three unique kinds. The ribs are mounted to the spar with bolts, while the skin is to be mounted with rivets. Figure 58 shows the 3D CAD drawing for the wing segment.

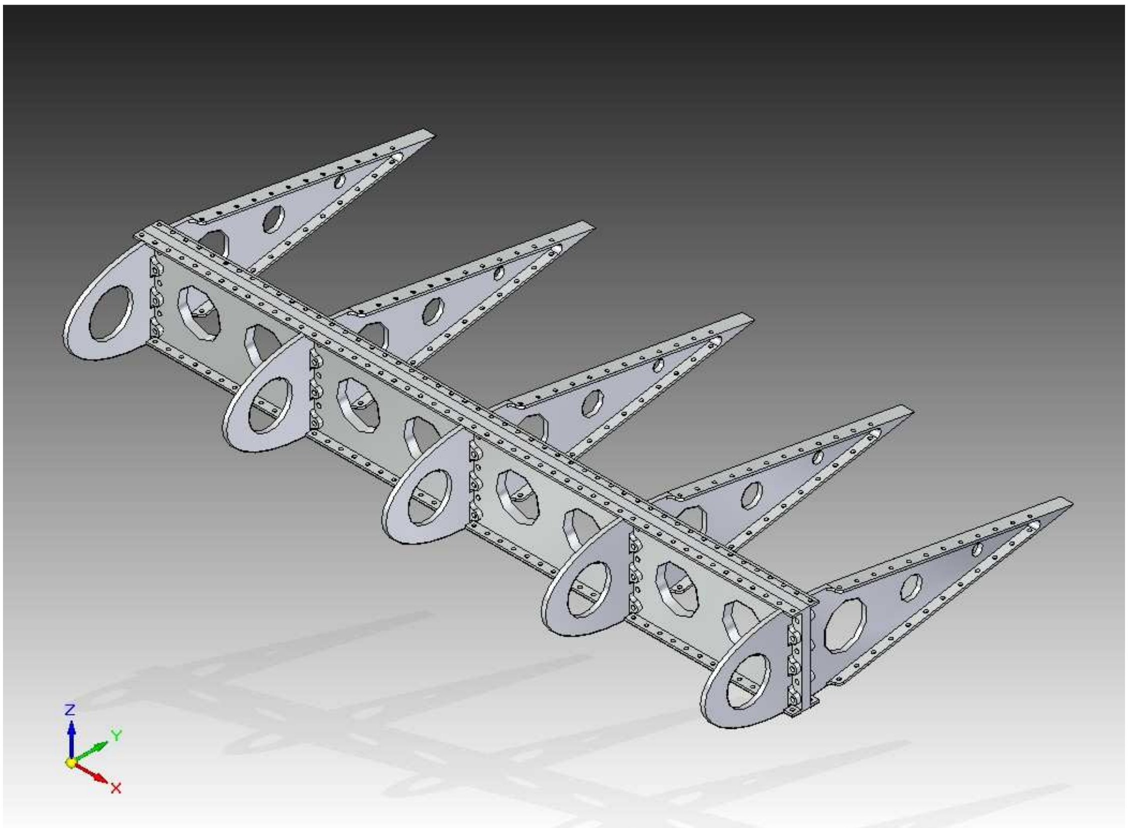

Figure 58: Computer aided drafting model of a cast wing alternative

Detailed multiview drafts of each part can be seen in Appendix C.2.

5.3.2 Sheet Metal Wing Description

The sheet metal wing is composed of a spar and ten ribs. Since the spar is thinner in this alternative than in the cast wing, the spar requires two stabilizer brackets that are mounted at the top and bottom of the spar. The stabilizers also help mount the skin to the wing. The total number of parts is twenty three, made up of four unique types. All fastening is done with rivets. The 3D CAD model for the sheet metal wing is shown below.

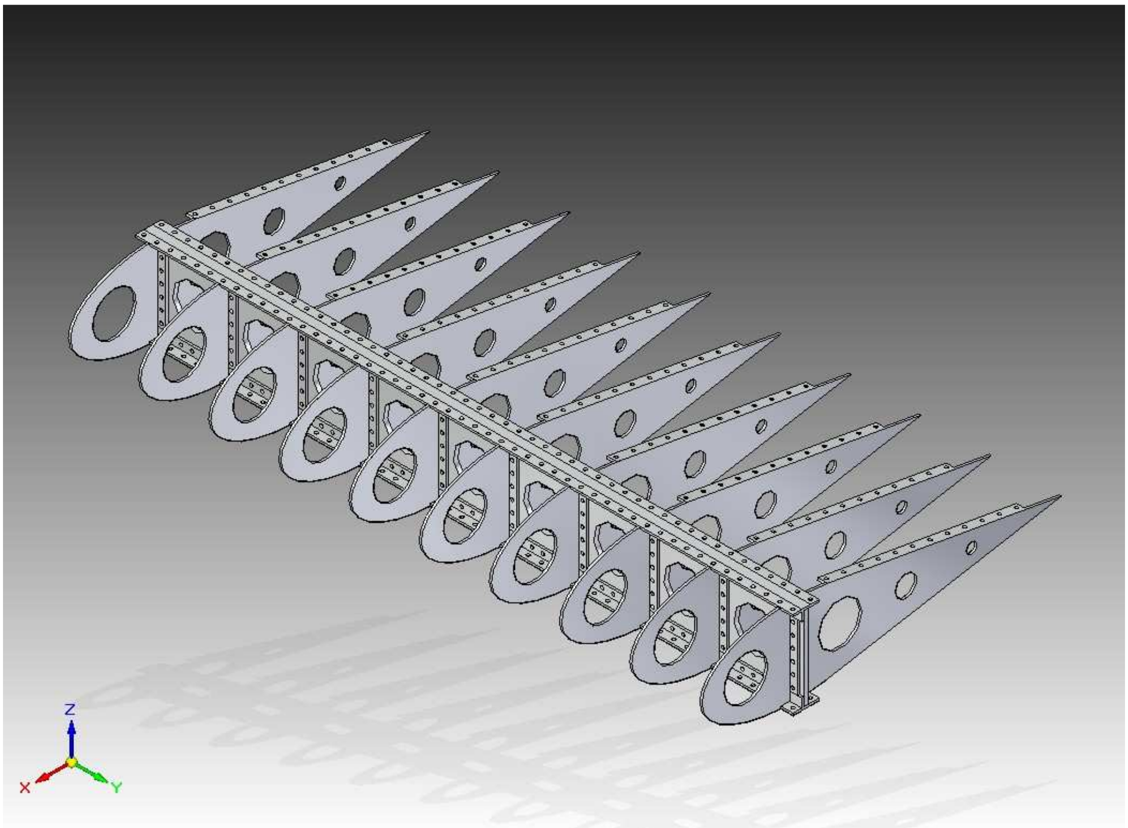

Figure 59: Computer aided drafting model of sheet metal wing alternative

Detailed multiview drafts of each part can be seen in Appendix C.3

5.4 Resource Inventory

<u>5.4.1 Fuel Resource Inventory</u>

The designer knows that all machines in both plants operate on grid electricity. The designer chooses the ideal grid electrical resources for Georgia and Missouri, shown below. These are extracted from the predetermined resource library discussed earlier.

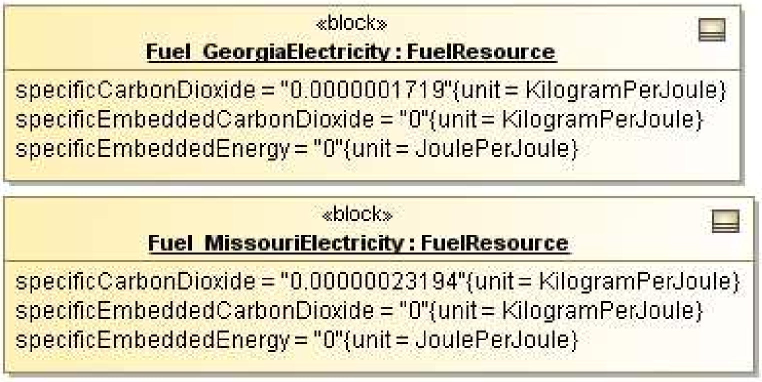

Figure 60: Fuel resource inventory for case study

5.4.2 Material Resource Inventory

The designer knows that the construction is made of aluminum, using steel fasteners. The designer constructs two instances of material resources based on existing LCI's and databases. The aluminum is based on the LCI for 1100 grade aluminum, which is almost pure aluminum, while the steel is based on generic, low carbon steel.(Govetto, 2008)(Kalpakjian & Schmid, 2003)

Figure 61: Solid material resource inventory for case study

The lubricant used for all of the machines is a generic, off the shelf lubricant. The designer looks up information about the lubricant from an LCA done on the lubricant from published sources.

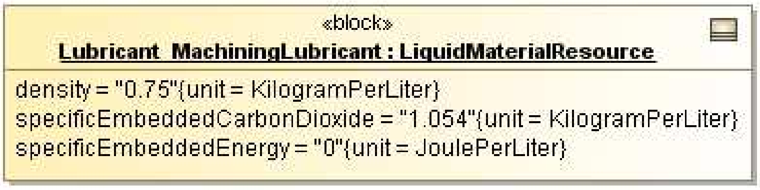

Figure 62: Liquid material resource inventory for case study

5.4.3 Machine Resource Inventory

The designer is unable to survey the machines at either location, so he assumes an ideal machine so that he can establish a baseline. The ideal machine is the same machine from Figure 46, using the lubricant in Figure 62. He creates two instances of the ideal machine, one with the fuel coming from Georgia's electrical grid, and the other from Missouri's grid.

5.4.4 Fastener Resource Inventory

Two types of fasteners are used in the wing segments. The first is a 5 mm course thread bolt. The second is a 4 mm blind rivet. The designer looks up properties about the fasteners from manufacturer websites and textbook tables. The resulting instances are shown below.(Shigley & Mischke, 1989)

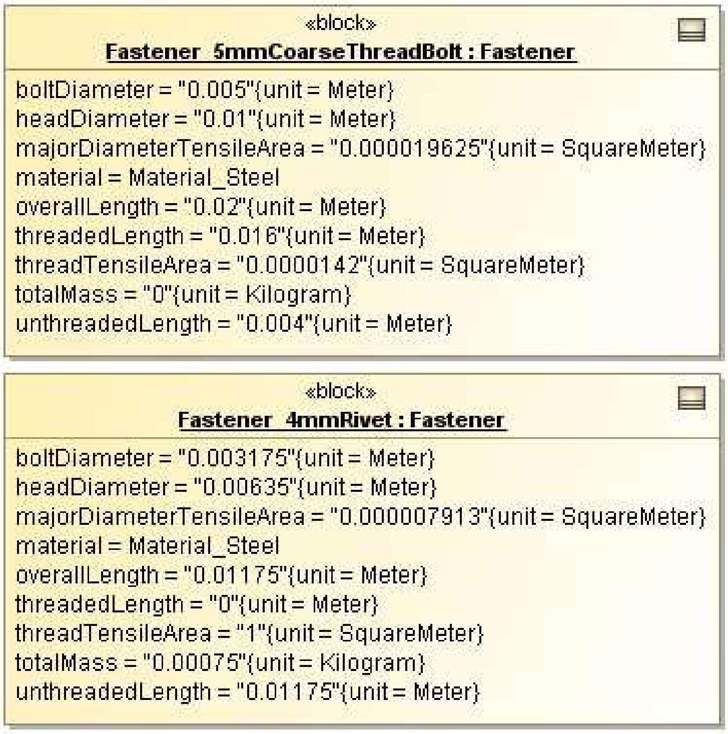

Figure 63: Fastener resource inventory for case study

5.5 Construction of Cast Wing Instance Scenario

5.5.1 Generating an Activity Space using Product Level Decomposition

The wing segment is treated as an assembly. The assembly is made up of eleven unit parts, of which three unique unit parts need to be defined. The three unique parts are the rib nose section, the rib tail section, and the spar.

The rib nose section is near-net-shaped with a die casting operation. After it is die cast, six holes are drilled to mount the nose to the spar. The rib tail section is also near-net-shaped with a die casting operation. Once cast, six mounting holes to connect the tail to the spar are drilled. Next, twenty four holes (twelve on each flange) are drilled to mount the skin to the wing. The spar is extruded in a cold extrusion operation. Once extruded, eight holes are machined into the spar to reduce weight. Next, sixty holes are drilled to mount the rib sections to the spar. Finally, 200 holes are drilled in the spar to mount the skin. Each rib nose section and rib tail section needs to be bolted to the spar. From this information, a product level decomposition of the wing segment assembly can be formulated. This decomposition is shown visually in Figure 64, with corresponding elements in Table 3.

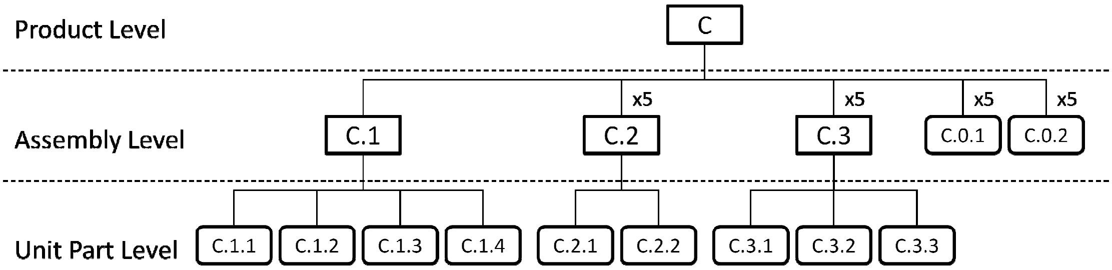

Figure 64: Cast wing Activity Space defined by product level decomposition

Table 3: Cast wing Activity Space element description

Index	Name	Type
C	Cast Wing	Assembly
C.0.1	Mount Nose Section	Operation
C.0.2	Mount Tail Section	Operation
C.1	Spar	Unit Part
C.1.1	Extrude Spar	Operation
C.1.2	Machine Large Spar Holes	Operation
C.1.3	Drill Spar Skin Holes	Operation
C.1.4	Drill Rib Mounting Holes	Operation
C.2	Rib Nose	Unit Part
C.2.1	Die Cast Nose	Operation
C.2.2	Drill Nose Mounting Holes	Operation
C.3	Rib Tail	Unit Part
C.3.1	Die Cast Tail	Operation
C.3.2	Drill Tail Mounting Holes	Operation
C.3.3	Drill Tail Skin Holes	Operation

The cast wing section's Activity Space contains thirty nine activities, of which eleven are unique. All thirty nine activities belong to the wing section, but to determine them directly would have been too difficult. Therefore, the assembly was first broken down into unit parts before the operations were defined.

5.5.2 Constructing the Enterprise Perspective Model

The major fabrication operations are performed at one manufacturing plant in Missouri, USA. The assembly plant in Georgia, USA not only assembles the product, but drills any holes used for mounting parts to the spar, not including skin. The Activity Space in Figure 64 can be organized into two plants, seen visually below.

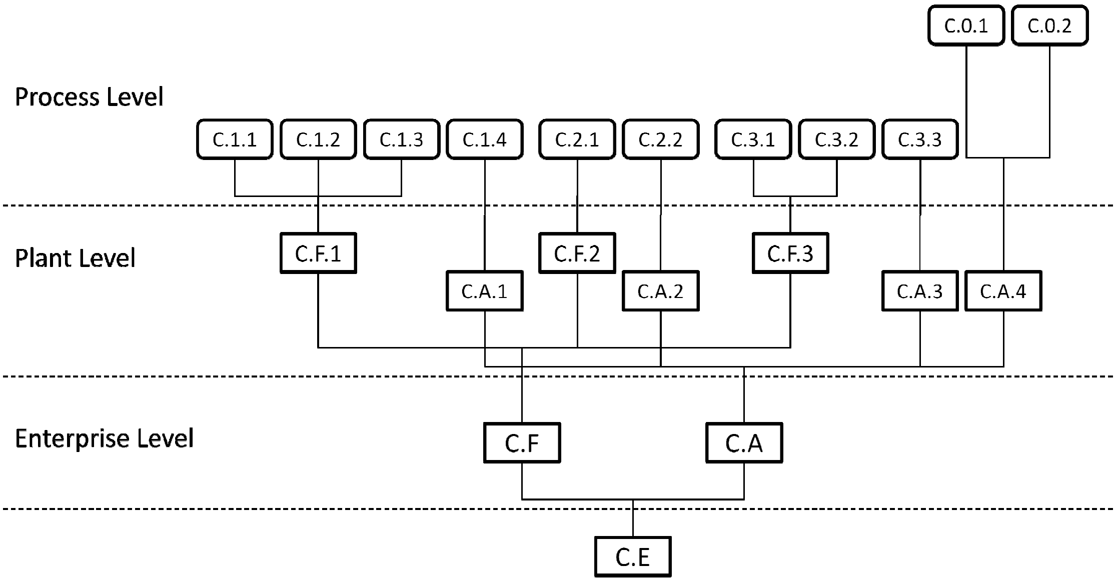

Figure 65: Cast wing organization from the enterprise perspective

Table 4: Cast wing enterprise perspective Activity Space element definition

Index	Description	Type
C.E	Cast Wing Enterprise	Enterprise
C.F	Cast Wing Fabrication Plant	Plant
C.F.1	Spar Fabrication	Process
C.F.2	Rib Nose Fabrication	Process
C.F.3	Rib Tail Fabrication	Process
C.A	Cast Wing Assembly Plant	Plant
C.A.1	Spar Mounting Hole Fabrication	Process
C.A.2	Rib Nose Mounting Hole Fabrication	Process
C.A.3	Rib Tail Mounting Hole Fabrication	Process
C.A.4	Cast Wing Assembly	Process

The enterprise perspective uses the same Activity Space from Figure 65, but with the product level perspective removed. The activities in the Activity Space remain unchanged, merely their assignment is changed.

5.5.3 Construction of Instance Model

The Activity Space from Figure 64 is first modeled as instances of assemblies, unit parts, and manufacturing operations. For each operation instance, the designer plugs in some known information. He extracts physical dimensions from inspecting geometry in the CAD file. He enters 1 s for the operation time as a placeholder. This does not affect the results since the machine is assumed ideal. He also assumes the ambient temperature in the each location is 80° F, or 300 K, and a typical aluminum extrusion temperature of 500 K (toward the upper bound of the cold extrusion limit). The instance model can be seen below. Green instances indicate the element is an operation, yellow instances indicate unit parts, while the red instance is the cast wing assembly.

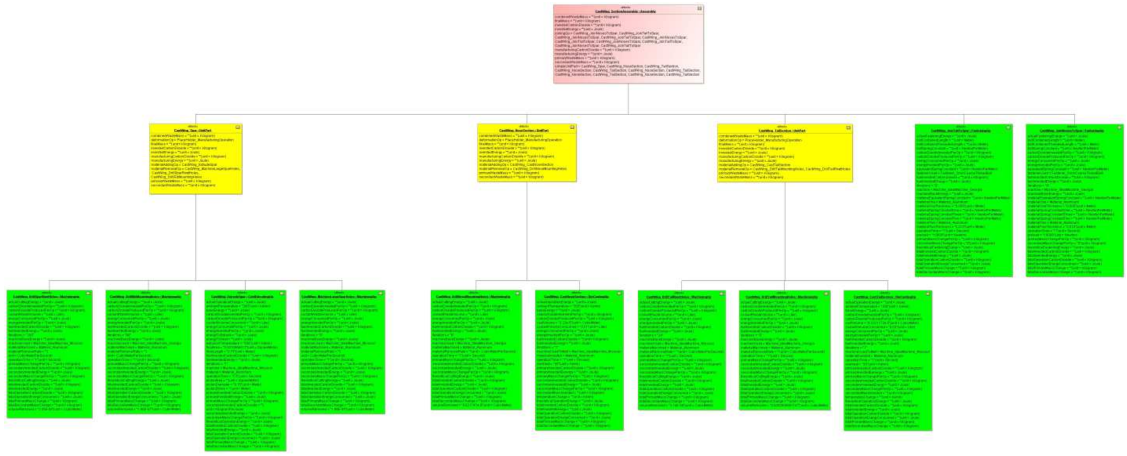

Figure 66: Cast wing instance model from product level perspective

Note the similarities between the instance model in Figure 64 and the Activity Space model in Figure 66. Detailed figures of each instance above can be found in Appendix B.1.

The same activity instances were then used to organize the model from the enterprise perspective. Below, the figure shows the instance model from the enterprise perspective with the operations still in green, processes and plants in yellow, and the entire enterprise in red.

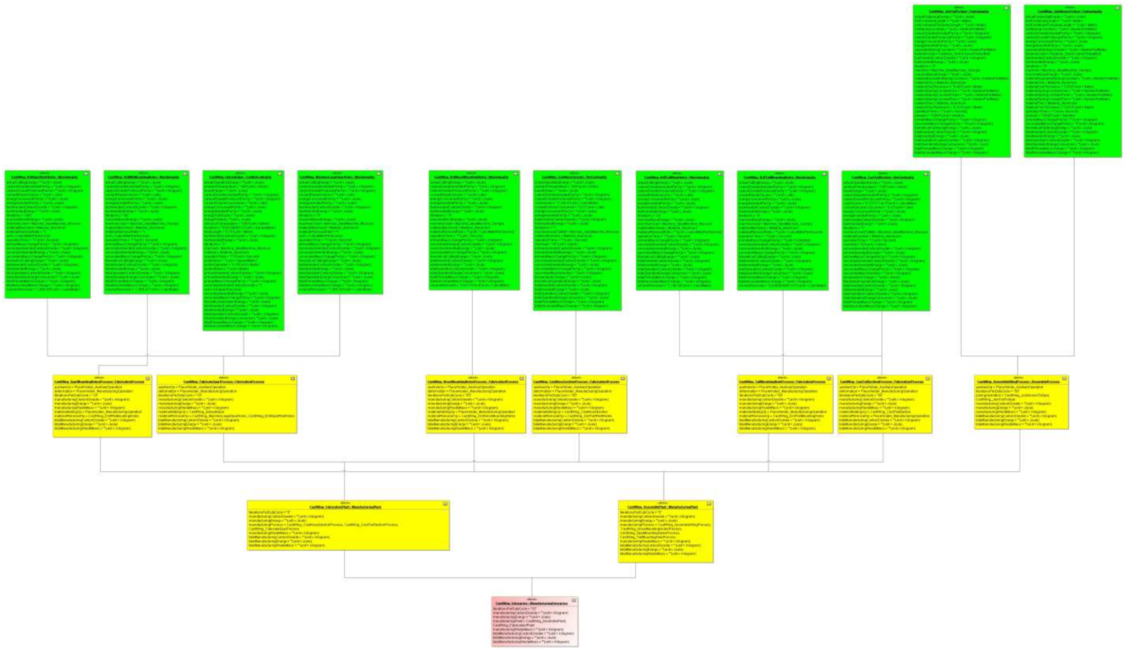

Figure 67: Cast wing instance model from the enterprise perspective

Again, note the similarities between Figure 65 and Figure 67. The instances of the operations are only defined once. Due to the object oriented modeling structure of SysML, the instances of the operations need only be defined once and can be reused over and over. Furthermore, the operations can be assigned to *both* elements from the product level and the enterprise perspectives without causing interference. A detailed view of each instance can be seen in Appendix B.1.

It took about 30 minutes to extract the necessary information out of the CAD file. Another 2 hours were spent creating the full product decomposition instance model, but only another 15 minutes were spent making the enterprise model. The reason creating the product decomposition model took so long was because all operations had to be defined for the first time. When it came time to create the enterprise model, all of the operations could be reused, reducing the time it took to create the instance model significantly.

Estimated time to get quantitative feedback on the system from both perspectives is 3 hours. This is assuming that the designer starts with a CAD file and the inventory of instances that came in the predetermined library.

5.5.4 Simulation and Results

The instance model of the cast wing segment from the product level perspective was executed using ParaMagic. The eight costs for a manufactured element were set as target values. The simulation took approximately 1 minute and 30 seconds to solve and return values. Below is shown the ParaMagic browser window after solving.

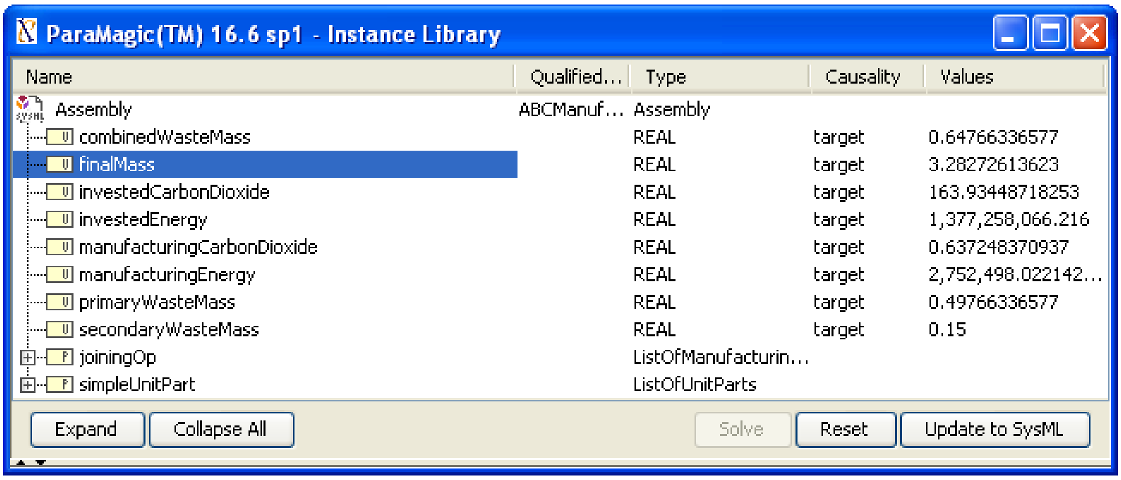

Figure 68: Cast wing from the product level perspective, fully solved ParaMagic browser

Highlighted is the final mass of the part. According to the model, the final part should be approximately 3.283 kg. According to the CAD file, the final wing mass should be 3.297 kg. The model calculated the final mass of the assembly based on information from the CAD file and some estimations and it was able to approximate the final mass to within 2 g or 0.4%. The discrepancy is actually slightly larger since the density of aluminum is estimated as 2700 kg/m^3 in the model, and 2717 kg/m^3 in the CAD file. This would lower the calculated mass, but the model also accounts for added mass of fasteners, bringing the model's estimated mass very close to the CAD estimated mass. Nevertheless, the closeness of mass values, even accounting for density and fastener discrepancy, adds validity to the model, supporting that at least some of the computations are done correctly and accurately. Having the mass calculation in the model come out to be so close to that of the CAD file supports the third validation criterion of the model, specifying that the model must return reasonably accurate results.

Next, the enterprise perspective was solved in SysML using ParaMagic. As mentioned earlier, the day-week-year duty cycle definition was used by the designer. He assumed that the fabrication plant could produce enough parts for ten wing sections per day, and the assembly plant could assemble ten wing sections per day. Each plant was in operation five days per week. The enterprise costs were to be calculated for fifty two weeks, or one year. The solution took approximately 1 minute and 45 seconds. Below is the solved ParaMagic browser window. Note the different costs for the different perspective.

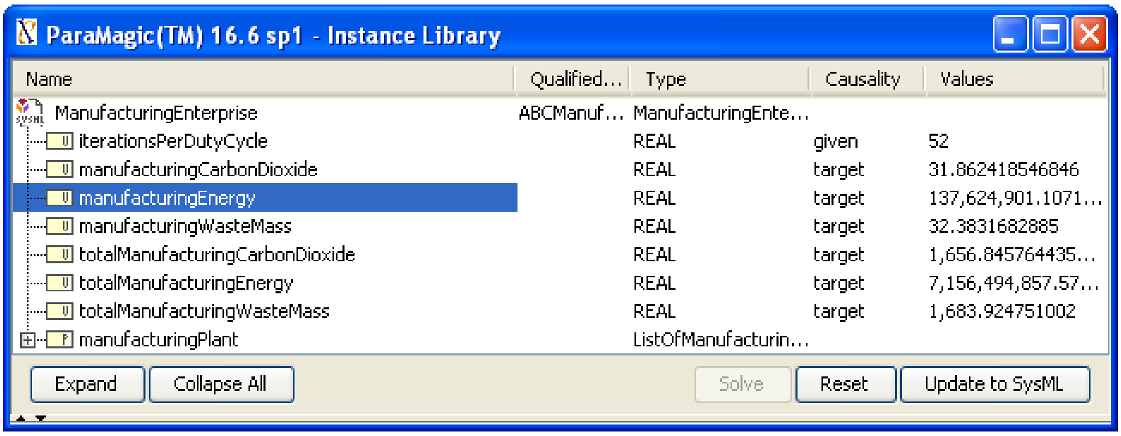

Figure 69: Cast wing from the enterprise perspective, fully solved ParaMagic browser

According to the results, just over 7.15 GJ of energy are consumed to produce 2600 wing sections per year. This is approximately 1988 kWh, which is a small but reasonable number that is not excessively large or excessively small. At this time, it is impossible to validate if this is a reasonably accurate number. The number is small since it only includes the manufacturing operations and does not include facilities costs, or costs associated with manufacturing any other products.

5.5.5 Constructing a Federated Model for the Cast Wing

The instance model created for the cast wing essentially represents a manufacturing bill of materials that one particular engineer may be concerned with. However, to create a federated model that integrates multiple engineering perspectives and focus areas, additional SysML diagrams must be used. As of yet, these additional diagrams cannot be executed by ParaMagic when built in MagicDraw. Nevertheless, they bring insight about the system beyond that which can be gathered just from the BDD's and IBD's already present in the cast wing example.

The additional diagrams derive information from the Activity Space diagram first introduced in Chapter 3, shown below in Figure 70.

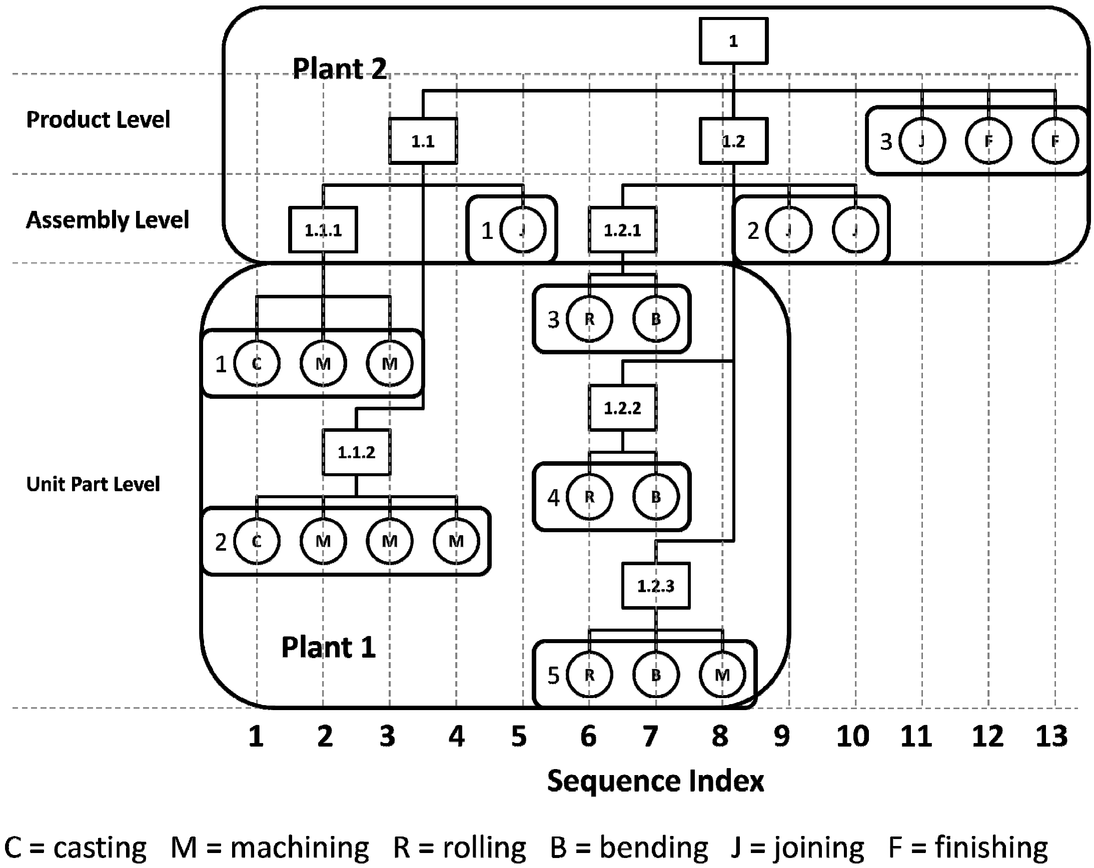

Figure 70: Basic Activity Space diagram

The first new perspective that can be seen here is some sort of sequential order, as indicated by the sequence index. For a process planning engineer, the order of operations is important. Therefore, the ABOOM Model must include a diagram that can indicate the order of operations or a process work flow, reflecting the sequential index dimension for the cast wing example. SysML's Activity Diagram (ACT) is capable of representing this process plan by modeling operations as actions, and structuring them in a Petri Net-like structure. The ACT for the cast wing process flow can be seen below. The indices of the actions correspond to the operations shown in Table 3.

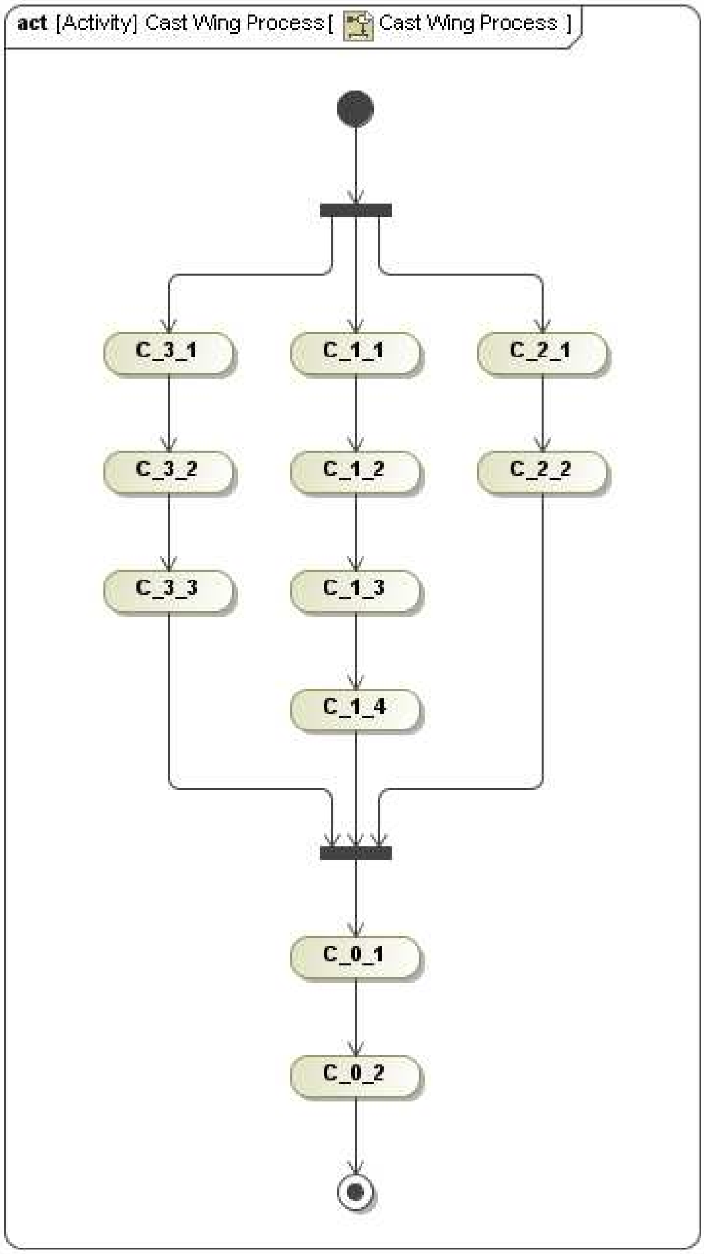

Figure 71: Cast wing activity diagram depicting process flow

The next engineering perspective that can be addressed with additional diagrams is the logistics engineering perspective. Logistics engineers would be interested in the physical flow of resources, products, and waste through a system. SysML is capable of representing this flow through the use of an Internal Block Diagram (IBD). In this case, the IBD shows flows of elements between and amongst elements contained by a particular block. For a logistics engineer interested in resource, waste, and product flow through the cast wing enterprise, the IBD shown below indicates to and from where these elements flow.

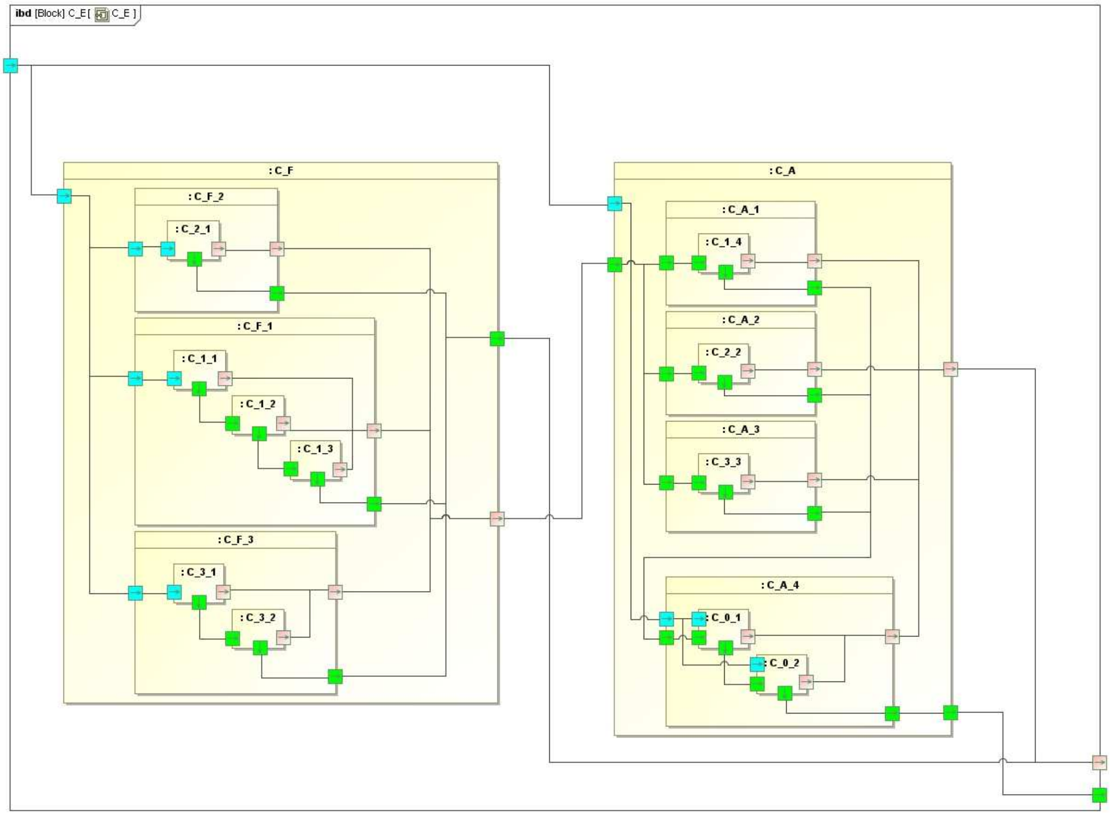

Figure 72: Internal block diagram depicting flow of elements in the cast wing example

As for the ACT, the index names of these elements correspond to the elements described in Table 3 and Table 4. Flow ports colored blue indicate flow of resources, while ports colored green show flow of product elements. Red indicates waste flow ports. Note how this IBD for the cast wing example is similar to the Activity Space diagram in Figure 70. Note how the Plant and Process boundaries in the general Activity Space diagram are mimicked in the IBD.

In total, a federated model for the cast wing includes information for the manufacturing bill of materials, operation ordering for a process plan, as well as logistical flow of resources, product elements, and waste through the cast wing system. This helps link together multiple engineering fields interested in the same system, each bringing some information that describes part of the system. This federated model is made possible by SysML's ability to model different parts of a system with different diagrams. Though these additional diagrams are not executable at this point, they do provide insight to the system that cannot be obtained strictly from the executable part of the ABOOM Model.

5.6 Construction of Sheet Metal Wing Instance Scenario

5.6.1 Generating an Activity Space using Product Level Decomposition

The wing section is an assembly made up of twenty three unit parts. Of the twenty three unit parts, four are unique. These parts are the spar, rib nose section, rib tail section, and a spar stabilizer. The wing is primarily made of rolled and bent sheet metal components. Aviation components are traditionally made of rolled and bent sheet metal because it is lighter than producing a structure out of cast components. According to the

CAD models, the sheet metal wing should be about 17% lighter than the cast component wing, which is a significant amount.

The nose section is rolled and stamped from an extruded billet before a mounting flange is bent and mounting holes are drilled. Similarly, the tail section is rolled from an extruded billet before it is stamped and with mounting flanges bent and holes drilled. The spar is an extruded piece of metal with large holes stamped in its body to reduce mass. Mounting holes are also drilled into the spar. The spar stabilizers are also extruded metal sections that have mounting holes for the spar and skin drilled into them. All components are riveted together with blind rivets. The decomposition of the sheet metal wing is shown visually in Figure 73, with the corresponding elements outlined in Table 5.

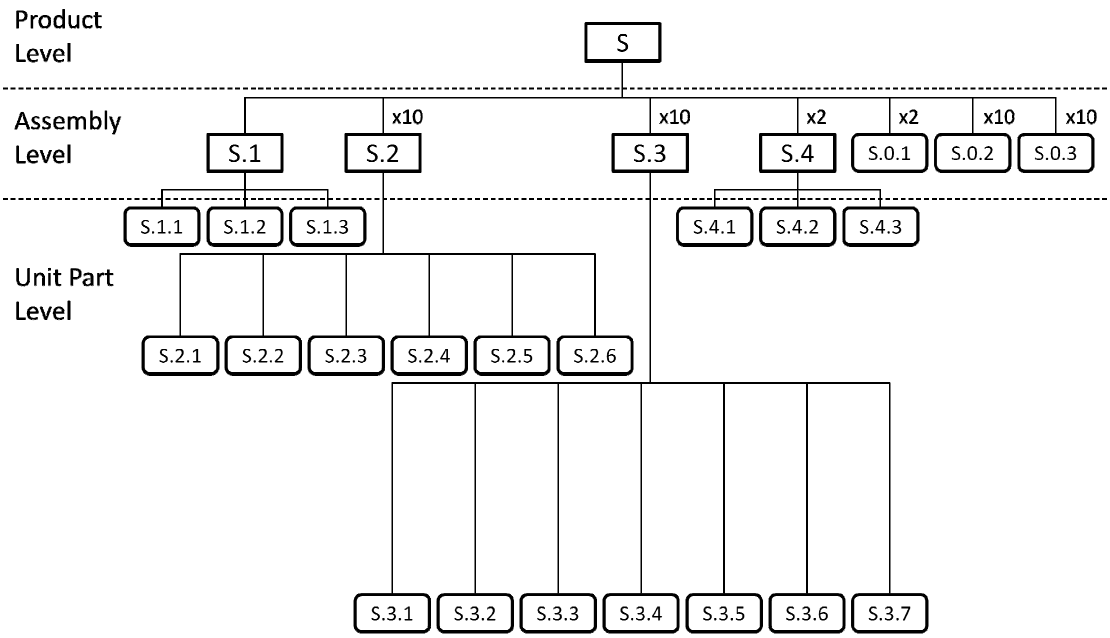

Figure 73: Sheet metal wing organization from product decomposition perspective

Table 5: Sheet metal wing Activity Space element definition

Index	Description	Type
S	Sheet Metal Wing Section	Assembly
S.0.1	Join Stabilizer to Spar	Operation
S.0.1	Join Rib Nose to Spar	Operation
S.0.3	Join Rib Tail to Spar	Operation
S.1	Spar	Unit Part
S.1.1	Extrude Spar	Operation
S.1.2	Stamp Large Spar Holes	Operation
S.1.3	Drill Spar Mounting Holes	Operation
S.2	Rib Nose Section	Unit Part
S.2.1	Extrude Blank Nose Billet	Operation
S.2.2	Roll Nose Sheet	Operation
S.2.3	Blank Nose Shape	Operation
S.2.4	Stamp Large Nose Hole	Operation
S.2.5	Bend Nose Mounting Flange	Operation
S.2.6	Drill Nose Mounting Holes	Operation
S.3	Tail Section	Unit Part
S.3.1	Extrued Blank Tail Billet	Operation
S.3.2	Roll Tail Sheet	Operation
S.3.3	Blank Tail Shape	Operation
S.3.4	Stamp Tail Holes	Operation
S.3.5	Bend Tail Mounting Flange	Operation
S.3.6	Bend Tail Skin Flanges	Operation
S.3.7	Drill Mounting Holes	Operation
S.4	Spar Stabilizer	Unit Part
S.4.1	Extrude Spar Stabilizer	Operation
S.4.2	Drill Stabilizer Skin Holes	Operation
S.4.3	Drill Stabilizer Mounting Holes	Operation

It is already clear that manufacturing a sheet metal wing requires many more operations. The final assembly requires 160 operations, of which twenty two are unique. Compare to the thirty nine total activities for the cast wing. It becomes clear that the compromise to making the wing lighter is increasing the number of operations four-fold. At this point, it is unclear to the designer which design is going to be optimal.

5.6.2 Constructing the Enterprise Perspective Model

Just like for the cast wing section, most of the fabrication occurs in the Missouri plant, while some final fabrication and assembly occurs in the Georgia plant.

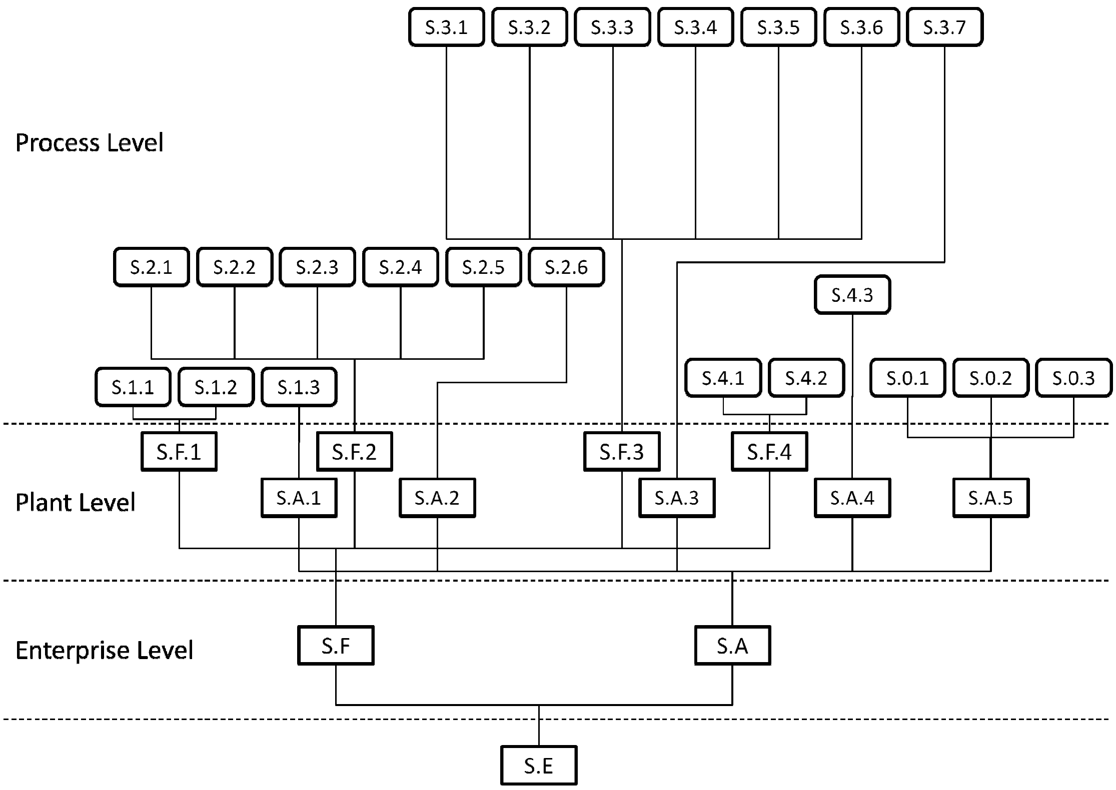

Figure 74: Sheet metal wing from the enterprise perspective

Table 6: Sheet metal wing enterprise perspective elements

Index	Description	Type
S.E	Sheet Metal Wing Enterprise	Enterprise
S.F	Fabrication Plant	Plant
S.F.1	Spar Fabrication	Process
S.F.2	Nose Fabrication	Process
S.F.3	Tail Fabrication	Process
S.F.4	Stabilizer Fabrication	Process
S.A	Assembly Plant	Plant
S.A.1	Spar Mounting Hole Fabrication	Process
S.A.2	Nose Mounting Hole Fabrication	Process
S.A.3	Tail Mounting Hole Fabrication	Process
S.A.4	Stabilizer Mounting Hole Fabrication	Process
S.A.5	Wing Assembly	Process

The enterprise perspective Activity Space uses the same activities as the product level perspective Activity Space, but the activities have been repositioned from Figure 73 to Figure 74 for clarity.

5.6.3 Construction of an Instance Model

Instance models for the sheet metal wing were made from both the product level decomposition perspective and the enterprise perspective. These instance diagrams are similar to that of Figure 66 and Figure 67, but are not shown here due to their increased size and complexity. All of the instances are shown in detail in Appendix B.2.

Extracting all of the necessary information out of the CAD file took about 30 minutes. Since the sheet metal wing contains many more unique instances over the cast wing, creating a full product level decomposition took about 3 hours. Since the activities are being reused, creating the enterprise perspective model took much less time, being built in about 20 minutes. The estimated time to get quantitative feedback on the system is 4 hours. This is the estimate starting with a CAD file and some instance library elements and solving two complete and separate instance models.

The same assumptions as for the cast wing were made. Additionally, the designer assumed a sheet metal roller diameter of 0.3 m or 30 cm.Figure 66

5.6.4 Simulation and Results

The sheet metal wing instance model from the product level perspective was executed using ParaMagic. The eight costs associated with a manufactured product were set as target values. These costs are:

- final part mass
- primary waste mass
- secondary waste mass
- combined waste mass
- manufacturing energy
- embodied energy
- manufacturing carbon dioxide
- embodied carbon dioxide
-

ParaMagic took about 8 minutes and 30 seconds to solve and return values. The solved ParaMagic browser window is shown in Figure 75.

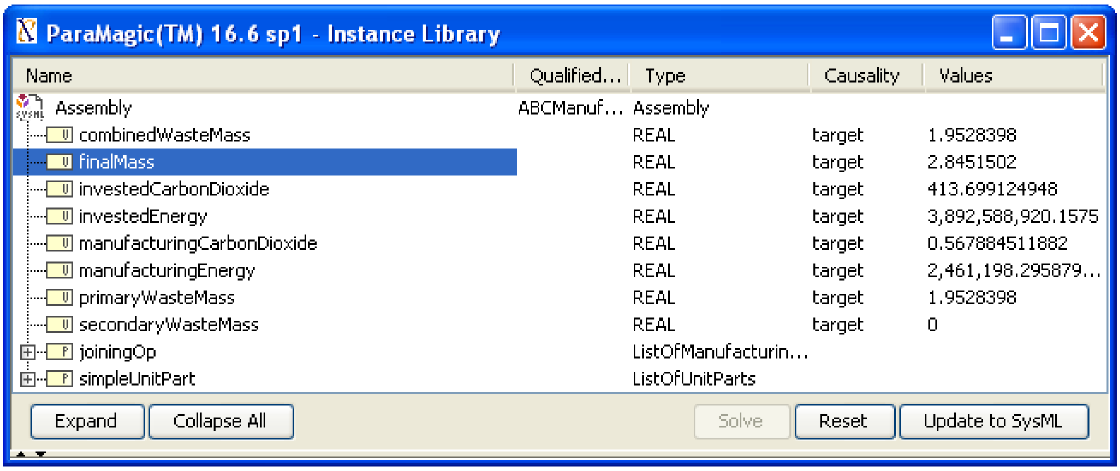

Figure 75: Sheet metal wing product level perspective fully solved ParaMagic browser

The CAD files estimated the mass of the assembly to be 2.731 kg, whereas the SysML model calculated the mass at 2.845 kg for an error of 4.2%. The error can be accounted for in that the density of aluminum varies slightly from the CAD file to the model, and the mass of the rivets adds some mass. Nevertheless, the values are very close, adding to the validity of calculations and supporting the third model validation criterion.

Next, the sheet metal wing instance model from the enterprise perspective was solved with ParaMagic. The six costs associated with a manufacturing enterprise were set as target values. These costs are:

- manufacturing carbon dioxide
- manufacturing energy
- manufacturing waste mass
- total manufacturing carbon dioxide
- total manufacturing energy
- total manufacturing waste mass

ParaMagic took about 10 minutes and 30 seconds to solve the model and return values. The solved ParaMagic browser can be seen in Figure 76.

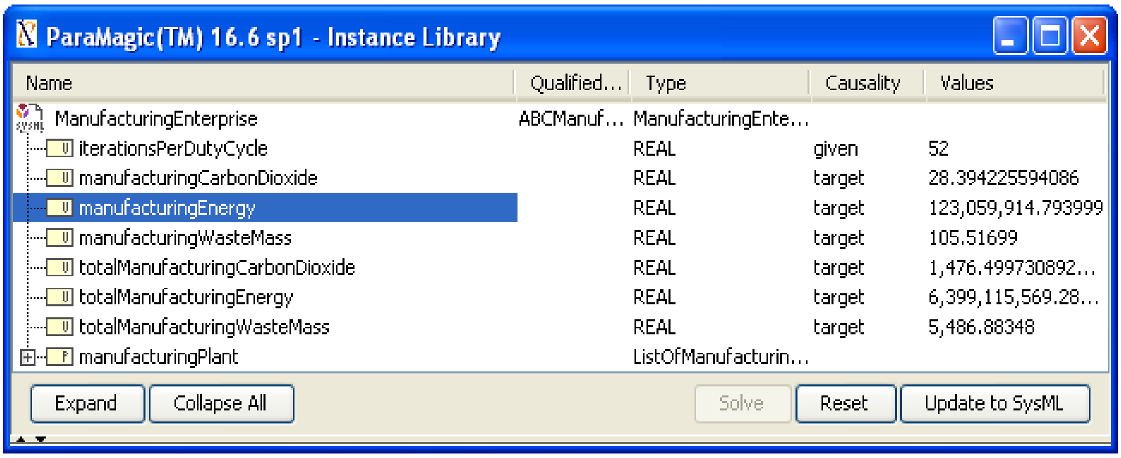

Figure 76: Sheet metal wing enterprise perspective fully solved ParaMagic browser

The enterprise consumed about 6.4 GJ of energy, approximately equal to 1778 kWh. As for the cast wing example, this number cannot be empirically validated at this time. However, the value is reasonable and is not excessively large or small, adding some validity to the model.

5.6.5 Constructing a Federated Model for the Sheet Metal Wing

As for the cast wing, the instance model described for the sheet metal wing represents a manufacturing bill of materials for the wing structure. Additional information needs to be modeled with SysML in the ABOOM Model in order to tie together logistical flow of elements as well as the sequential order of operations for the process plan. Just like for the cast wing example, a SysML ACT diagram can be used to define the order of activities during sheet metal wing manufacturing. As before, the index names correspond to elements defined in Table 5.

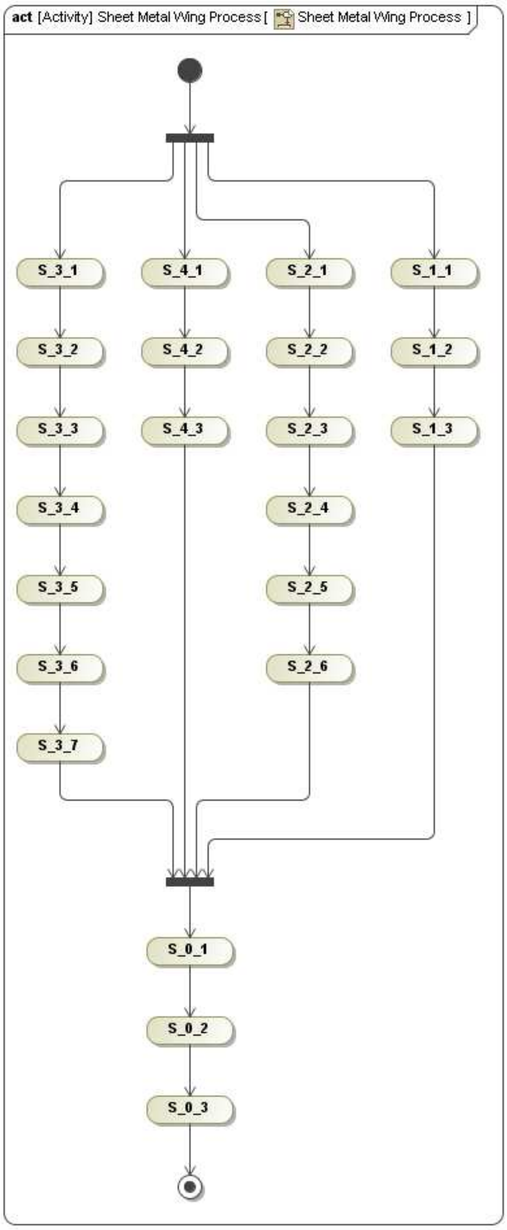

Figure 77: Activity diagram showing order of activities for the sheet metal wing example

Furthermore, an IBD can be used to describe the actual flow of resources, waste, and product elements for the sheet metal wing.

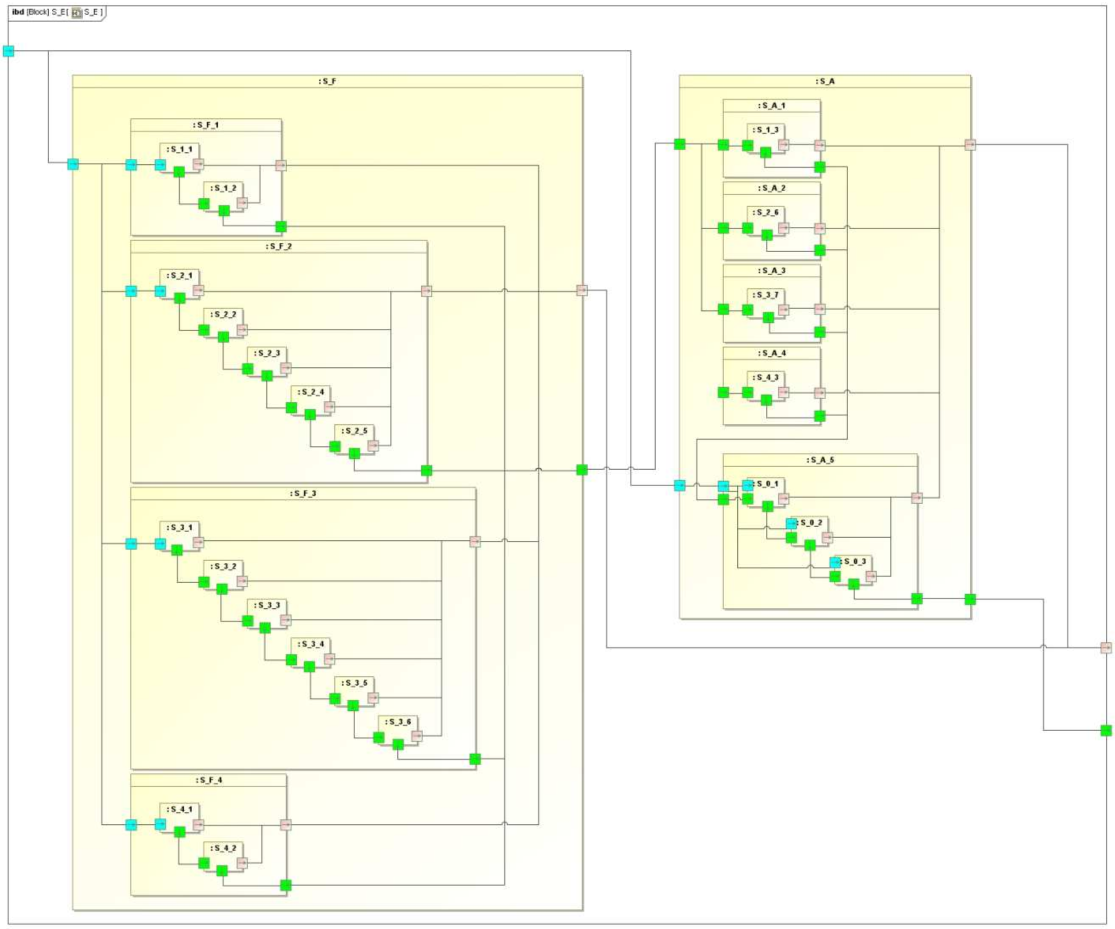

Figure 78: Internal block diagram showing logistical flow of elements in the sheet metal wing system

As with the cast wing example, the addition of two diagrams helps bring further insight into the system of interest. This also helps to tie together multiple engineering areas in a single model.

Though an ACT and an IBD were used to represent a process plan and a work flow, these are by no means the only way to represent this information. Each diagram highlights a particular characteristic of the system. Using multiple diagrams, even to describe the same part of the system from the same perspective helps to refine the description of that system. Additional ACT's and IBD's could be used to more thoroughly define the process plan or the work flow. Furthermore, other diagrams can be used to define other elements of the system interesting to different engineering stakeholders. For instance, a sequence diagram can be used to combine information from the ACT process plan diagram and the IBD work flow diagram. Use case diagrams can be useful for floor managers for determining the number of employees that need to be present to perform a certain operation or man a process line.

Ultimately, creating these other diagrams and representing the information that they can contain is outside of the scope of this thesis. The examples shown for the cast wing and the sheet metal wing are to illustrate how SysML would be capable of integrating the executable part of the ABOOM Model with other areas of interest for different stakeholders.

5.7 Comparison of Results and Design Selection

The results from the cast wing simulation and the sheet metal wing simulation were compared. First, the product level perspectives were compared. Table 7 shows the side-by-side comparison of the eight costs, their actual and percent difference.

Table 7: Comparison of cast to sheet metal wing from product level perspective

Cost	Cast Wing	Sheet Metal Wing	Δ(Cast-Sheet)	Unit
Embodied CO_2	163.934	413.699	-249.765	kg
Embodied Energy	1,377,000,000	3,893,000,000	-2,515,000,000	J
Manufacturing CO_2	0.637	0.568	0.069	kg
Manufacturing Energy	2,752,000	2,461,000	291,300	J
Primary Waste Mass	0.498	2.953	-2.455	kg
Secondary Waste Mass	0.150	0.000	0.150	kg
Combined Waste Mass	0.648	1.953	-1.305	kg
Final Assembly Mass	3.283	2.845	0.438	kg

It can be seen that the sheet metal wing did better on manufacturing costs and final mass. The cast wing did have lower waste mass and lower embodied costs. The secondary waste mass should be zero for both the cast and sheet metal wings, however a small amount of lubricant was assumed to be consumed by the casting processes in the cast wing case. These results for the designer are inconclusive, so the designer compares the enterprise costs to make the final decision.

Table 8: Comparison of cast to sheet metal wing from enterprise perspective

Cost	Cast Wing	Sheet Metal Wing	Δ (Cast-Sheet)	Unit
Tot. Manufacturing CO2	1,656	1,476	180	kg
Tot. Manufacturing Energy	7,156,000	6,399,115,000	757,379,000	J
Tot. Waste Mass	1,683	5,486	-3,802	kg

It can be seen that when the manufacturing process is looked at specifically, the sheet metal wing consumes less energy and produces less carbon dioxide during the year, though three times the waste mass is produced.

The sheet metal wing seems to be better because of its lower final mass and lower manufacturing costs. The embodied costs and waste mass are now the issue. Analyzing the results, it becomes clear that the reason the sheet metal wing had so much more in embodied costs is because it produced a significantly greater amount of waste mass. Reducing waste mass for the sheet metal wing would reduce embodied costs, making the sheet metal wing the clear choice.

Based on these results, the designer chooses the sheet metal wing as the optimal choice.

5.8 Conclusions from Hypothetical Case Study

The overall conclusion is that the SysML model and ParaMagic were successfully able to model and simulate two scenarios, giving quantitative feedback to the environmental impacts of each scenario.

Construction of the instance model was a little time consuming and tedious. Creating the appropriate number of instances did not take long, however filling slots in the instances with values was time consuming. This was because many of the input values had to be extracted from a CAD file and entered into the instance model manually. There is potential for this step to be automated. Computer aided process planning tools already perform a similar task where they extract geometry and material information out of a CAD file and generate input values for the machine. Once the Activity Space for each instance model was created, grouping the operations into a new perspective was not time consuming. This indicates that there is an initial time investment required to generate an Activity Space, but analysis occurs quickly afterwards.

Solve times were generally short, but not instantaneous. It appeared that the solve time increased proportionally to the number of operations, but the exact relation is not clear. For the assembly level analysis, solve time appeared to be somewhat directly proportional, solving a system of 4.1 times the number of activities in 5.7 times the amount of time. As an experiment, the two assemblies were said to be part of one product. This did not change the total number of operations and merely added one extra level to the instance model. Solve time for the combined 200 operations took approximately 35 minutes, whereas solving for 160 operations took between 8 and 9 minutes and 40 operations took between one and two minutes. This indicates that adding a new organizational layer increases the solve time exponentially. It would seem solving a four tier model (operation, unit part, assembly, product) takes much longer than solving a three tier model (operation, unit part, assembly), however there is some conflicting data. The enterprise perspective is a four tiered analysis, and it solves only slightly slower than the three tiered product level analysis. It would seem that solve time is proportional to both number of operations and levels of organization. The exact relationship cannot be determined from this case study.

In terms of usability and creating models quickly, it was said in Chapter 2 that the baseline for usability would be Homer. The ABOOM Model took on the order of a few hours to create. This is comparable to the amount of time it takes to create a model in Homer. A model in Homer requires seconds to several minutes to solve, which is comparable to the ABOOM Model using ParaMagic. Creating new elements in the

ABOOM Model takes a similar amount of time as creating new elements in Homer, but the user interface with Homer is superior. Overall, the ABOOM Model is assumed to have the same usability as Homer.

6 Final Summary and Conclusions

6.1 First Hypothesis

The first hypothesis states that SysML is capable of creating an Activity-Based Costing model of a manufacturing system. This is shown to be the case in Chapter 4 where an executable ABC model is constructed. This is done by creating an organizational modeling structure, based on fundamental ABC practices. This structure, called an Activity Space, is defined in Chapter 3 and is used the organizational backbone of the model described in Chapter 4. Using the Activity Space as a framework, SysML is capable of representing an ABC model of a manufacturing system. The final product is called an Activity-Based Object Oriented Manufacturing Model, or an ABOOM Model. The first hypothesis is upheld.

6.2 Second Hypothesis

The second hypothesis states that a SysML model of a manufacturing process is capable of simulating the system and returning meaningful results through the use of a third party solver. The solver used is Mathematica, which is accessed by a SysML plug in called ParaMagic. Chapter 5 demonstrates how SysML, ParaMagic, and Mathematica work together to simulate two alternative scenarios, returning results. These results need to be meaningful, and this was tested using three validation criteria. In the end, it was determined that the second hypothesis was upheld according to these three criteria.

6.2.1 First Validation Criterion

The first validation criterion states that the model should not violate any fundamental laws of physics. Chapter 4, Section 4.9.1 discusses how the ABOOM Model uses widely accepted mathematical models in calculating results. It is assumed that these accepted mathematical models do not violate any fundamental laws, so it is assumed that the ABOOM Model, using these mathematical models, also does not violate any fundamental laws.

6.2.2 Second Validation Criterion

The second validation criterion states that the ABOOM Model should distinguish amongst different scenarios adequately. Chapter 4, Section 4.9.2 shows how the ABOOM Model does this by using a parametric approach with a wide variety of possible inputs. Furthermore, the model satisfies this criterion with a wide selection of structural elements that can be used to uniquely define various parts of a system. The ABOOM Model is shown to adequately distinguish amongst different scenarios.

6.2.3 Third Validation Criterion

The third validation criterion states that results calculated by the ABOOM Model should be reasonable close to empirical results. Chapter 4, Section 4.9.3 discusses how the model could be validated with respect to this criterion. This is done with a laboratory experiment that measures environmental burdens produced during a manufacturing process. However, this experiment alone did not completely validate the model. This is because at this time it is impossible to validate all parts of the model. Rather, this experiment provides a template for how to perform a similar experiment for other aspects of the ABOOM Model. For the particular experiment performed, the ABOOM Model was found to estimate environmental burdens with reasonable accuracy. The third criterion is assumed upheld based on this experiment.

6.3 Third Hypothesis

The third hypothesis addresses the usability of the ABOOM Model. Usability is difficult to assess objectively, so the ABOOM Model was compared to a structurally similar existing assessment tool. The tool the ABOOM Model was compared to is Homer, an energy assessment tool developed by the National Renewable Energy Labs (NREL). In terms of time it takes to construct a model of a new scenario, Homer and the ABOOM Model both take about the same order of time, which is on the order of a few hours. In terms of solve time, a reasonably sized Homer model takes on the order of minutes to solve, which is comparable to the time it takes to solve a reasonably sized ABOOM Model. The one shortcoming of the ABOOM Model with respect to usability was the user interface. Homer has a custom designed user interface that prompts a user for all the necessary information. The ABOOM Model is modified directly in SysML where prompts would have to appear as text in comment boxes or not at all. Overall, SysML allows for greater transparency and traceability in the ABOOM Model, which Homer does not provide its user, but Homer is more visually appealing.

An important criterion of being usable, the ABOOM Model needed to be able to be solved with off-the-shelf solvers. This was shown to be the case with the use of ParaMagic. ParaMagic was successfully able to calculate numerical results for various scenarios in Chapter 4, Section 4.9 and Chapter 5. Being able to use an off-the-shelf solver meant that the user or designer did not need to custom build a solver to execute the ABOOM Model. This made the ABOOM Model more usable. Ultimately, it is found that the ABOOM Model is usable, and improves in usability with experience.

Appendix

Appendix A: SysML Model Elements

A.1 Value Types

Table A 1: List of value types used and their units

Value Type	Unit
Angle	radian
AngularVelocity	radian per second
CrossSectionalArea	meter squared
DistanceSpecificWorkEnergy	joule per meter
EmissionMass	kilogram
EnergySpecificEmissionMass	kilogram per joule
EnergySpecificEnergy	joule per joule (provided)
Force	Newton
Length	meter
LiquidFlowRate	liter per second
LiquidVolume	liter
LiquidVolumeSpecificWorkEnergy	joule per liter
MassSpecificDensity	kilogram per meter cubed
MassSpecificEmissionMass	kilogram (of emission) per kilogram
MassSpecificWorkEnergy	joule per kilogram
MaterialMass	kilogram
MaterialRemovalRate	meter cubed per second
MaterialVolume	meter cubed
ModulusOfElasticity	Pascal
Power	Watt
SolidVolumeSpecificWorkEnergy	joule per meter cubed
SpecificHeat	joule per kilogram
SpecificHeatCapacity	joule per kilogram per Kelvin
SpringConstant	Newton per meter
Stress	Pascal
Temperature	Kelvin
Time	second
TransportDistance	meter
Velocity	meter per second
VolumeSpecificDensity	kilogram per liter
VolumeSpecificEmissionMass	kilogram (of emission) per liter
WorkEnergy	joule

A.2 Constraints

Table A 2: List of mathematical equations used(Kalpakjian & Schmid, 2001)(Kalpakjian & Schmid, 2003)(Tlusty, 2000)(DeGarmo, Black, & Kohser, 1997)

Constraint Type	Equation
Add2	$total = a + b$
Add3	$total = a + b + c$
Add4	$total = a + b + c$
AddVector	$total = \sum a$
AddVector2	$total = \sum a + \sum b$
AddVector3	$total = \sum a + \sum b + \sum c$
AddVector9	$total = \sum a + \sum b + \sum c + \sum d + \sum e + \sum f + \sum g + \sum h + \sum i$
Average2	$total = \frac{a + b}{2}$
BendingEnergyEq	$E = \frac{1.265(UTS)Lt^2d}{W}$
BendingStrokeEq	$d = \frac{W}{2tan(\theta/_2)}$
BoltSpringConstantEq	$k_b = \frac{A_d A_t E_b}{A_d l_t + A_t l_d}$
CircularAreaEq	$A = \frac{\pi D^2}{4}$
ColdExtrusionEnergyEq	$E = \frac{1.707 A_i L_i K \ln\left(\frac{A_i}{A_f}\right)^{n+1}}{n+1}$
ColdRollingEnergyEq	$E = \frac{0.575 L^2 wk \left\|ln\left(\frac{h_f}{h_b}\right)\right\|^n \left(1 + \frac{\mu L}{2h_{avg}}\right) h_b l_b}{(n+1)Rh_{avg}}$
Divide2	$total = \frac{a}{b}$
FasteningEnergyEq	$E = \frac{1}{2}\frac{F^2}{k}$
HeatingEnergyEq	$E = mc(T_f - T_i)$
HotExtrusionEnergyEq	$E = 1.707 A_i L_i C \left(\frac{6v}{D_i}\right)^m \ln\left(\frac{A_i}{A_f}\right)^{m+1}$
MaterialSpringConstantEq1	$k = \frac{0.577\pi Ed}{\ln\left[\frac{(1.15t + D - d)(D + d)}{(1.15t + D + d)(D - d)}\right]}$

Table A 2 continued

Constraint Type	Equation
MaterialSpringConstantEq2	$k = \frac{0.577\pi E_2 d}{\ln\left[\frac{\left(1.15\left(\frac{t_2 - t_1}{2}\right) + (1.15t_2 + D) - d\right)\left((1.15t_2 + D) + d\right)}{\left(1.15\left(\frac{t_2 - t_1}{2}\right) + (1.15t_2 + D) + d\right)\left((1.15t_2 + D) - d\right)}\right]}$
MaterialSpringConstantEq3	$k = \frac{0.577\pi E_2 d}{\ln\left[\frac{\left(1.15\left(\frac{t_1 + t_2}{2}\right) + D - d\right)(D + d)}{\left(1.15\left(\frac{t_1 + t_2}{2}\right) + D + d\right)(D - d)}\right]}$
MeltingEnergyEq	$E = m\left(c_S \Delta T + \Delta H_f + c_L T_{overheat}\right)$
Multiply2	$total = a \times b$
Multiply3	$total = a \times b \times c$
Multiply4	$total = a \times b \times c \times d$
PlantManufacturingProcessCostEq	$C = \sum C_{fabrication} + \sum C_{assembly}$
RollerAngularVelocityEq	$\omega = \frac{h_b l_b t}{h_{avg} R}$
RollingContactLengthEq	$l = \sqrt{R\left(h_b - h_f\right)}$
SeriesSpringConstant3	$k = \left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}\right)^{-1}$
ShearingEnergyEq	$E = 0.7t^2 L(UTS)$
Subtract2	$total = a - b$
Subtract3	$total = a - b - c$
Subtract4	$total = a - b - c - d$
TruncatedConeDiameterEq	$D_{new} = 1.154t + D$
UnitPartFinalMassEq	$m_{unitPart} = \sum \Delta m_{sandCasting} + \sum \Delta m_{dieCasting} + \sum \Delta m_{hotExtrusion} + \sum \Delta m_{coldExtrusion} - \sum \Delta m_{sawing} - \sum \Delta m_{shearing} - \sum \Delta m_{materialRemoval}$

A.3 Resources

Table A 3: List of idealized fuel resources (World Coal Institute, 2009)(Energy Information Administration, 2009)(Environmental Protection Agency, 2009)(Wikipedia, 2009)

Fuel	CO2 Emission Rate (kg/J)
Petroleum Products	
Aviation Gas	7.90781E-09
Distillate Fuel (No. 1, 2, 4 fuel oil and Diesel)	9.64361E-09
Jet Fuel	9.08827E-09
Kerosene	9.2787E-09
Liquefied Petroleum Gas	5.51673E-09
Motor Gasoline	8.42868E-09
Petroleum Coke	1.39575E-08
Residual Fuel (No. 5 and 6 Fuel Oil)	1.12157E-08
Average Petroleum	9.37962E-09
Natural Gas (Gaseous Fuels)	
Methane	5.01378E-08
Flare Gas	5.76269E-08
Natural Gas (pipeline)	5.19546E-08
Propane	5.45813E-09
Average Gaseous Fuel	4.12943E-08
Coal	
Anthracite	2.44925E-06
Bituminous	2.12453E-06
Subbituminous	1.60091E-06
Lignite	1.20269E-06
Average Coal	1.84434E-06
Renewable Sources	
Geothermal Energy	0
Wind	0
Photovoltaic and Solar Thermal	0
Hydropower	0
Tires and Tire Derived Fuel	2.65389E-06
Wood and Wood Waste	1.64231E-06
Municipal Solid Waste	8.61221E-07

Table A 4: Electrical grid fuel resources for the United States, organized by region and state(Energy Information Administration, 2009)(Environmental Protection Agency, 2009)

State or Region	Carbon Dioxide Emissions (kg/Joule)
New England	*1.2389E-07*
Connecticut	1.1861E-07
Maine	1.0722E-07
Massachusetts	1.6083E-07
New Hampshire	8.6111E-08
Rhode Island	1.2417E-07
Vermont	3.6111E-09
Mid Atlantic	*1.3083E-07*
New Jersey	8.8889E-08
New York	1.0806E-07
Pennsylvania	1.5944E-07
East-North Central	*2.0556E-07*
Illinois	1.4667E-07
Indiana	2.6167E-07
Michigan	1.9917E-07
Ohio	2.2694E-07
Wisconsin	2.0694E-07
West-North Central	*2.1778E-07*
Iowa	2.3722E-07
Kansas	2.1222E-07
Minnesota	1.9194E-07
Missouri	2.3194E-07
Nebraska	1.7639E-07
North Dakota	2.8250E-07
South Dakota	1.0056E-07
South Atlantic	*1.7000E-07*
Delaware	2.3056E-07
Florida	1.7556E-07
Georgia	1.7194E-07
Maryland	1.7222E-07
North Carolina	1.5639E-07
South Carolina	1.0500E-07
Virginia	1.4667E-07
West Virginia	2.4917E-07

Table A 4 continued

State or Region	Carbon Dioxide Emissions (kg/Joule)
East-South Central	*1.8806E-07*
Alabama	1.6528E-07
Kentucky	2.5306E-07
Mississippi	1.6306E-07
Tennessee	1.6333E-07
West-South Central	*1.8000E-07*
Arkansas	1.6222E-07
Louisiana	1.4833E-07
Oklahoma	2.1694E-07
Texas	1.8444E-07
Mountain	1.9694E-07
Arizona	1.3222E-07
Colorodo	2.4250E-07
Idaho	3.6111E-09
Montana	1.8056E-07
Nevada	1.9111E-07
New Mexico	2.5417E-07
Utah	2.4389E-07
Wyoming	2.7028E-07
Pacific Contiguous	*5.6389E-08*
California	7.6389E-08
Oregon	3.5278E-08
Washington	3.0833E-08
Pacific Non-Contiguous	*1.9639E-07*
Alaska	1.7389E-07
Hawaii	2.0944E-07
US Average	*1.6833E-07*

A.4 Manufacturing Operations

A.4.1 Sand Casting Operation

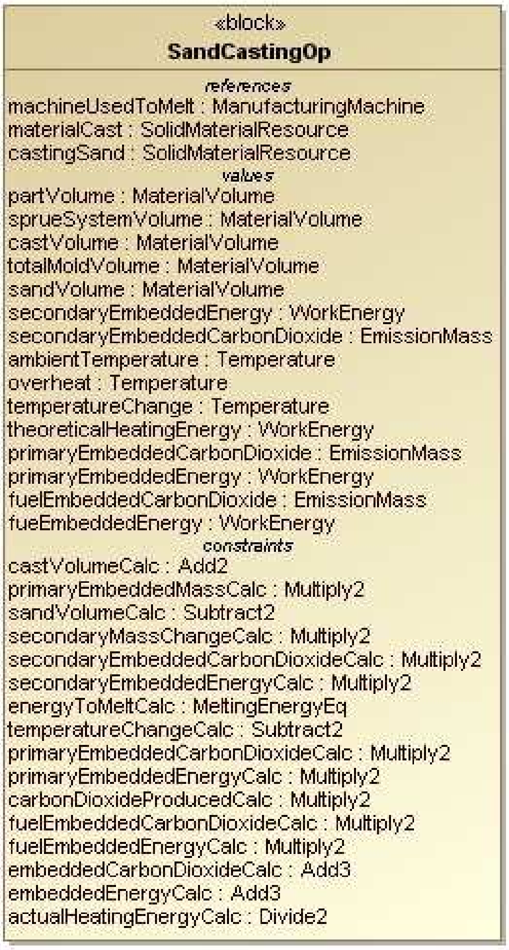

Figure A 1: Sand casting operation block

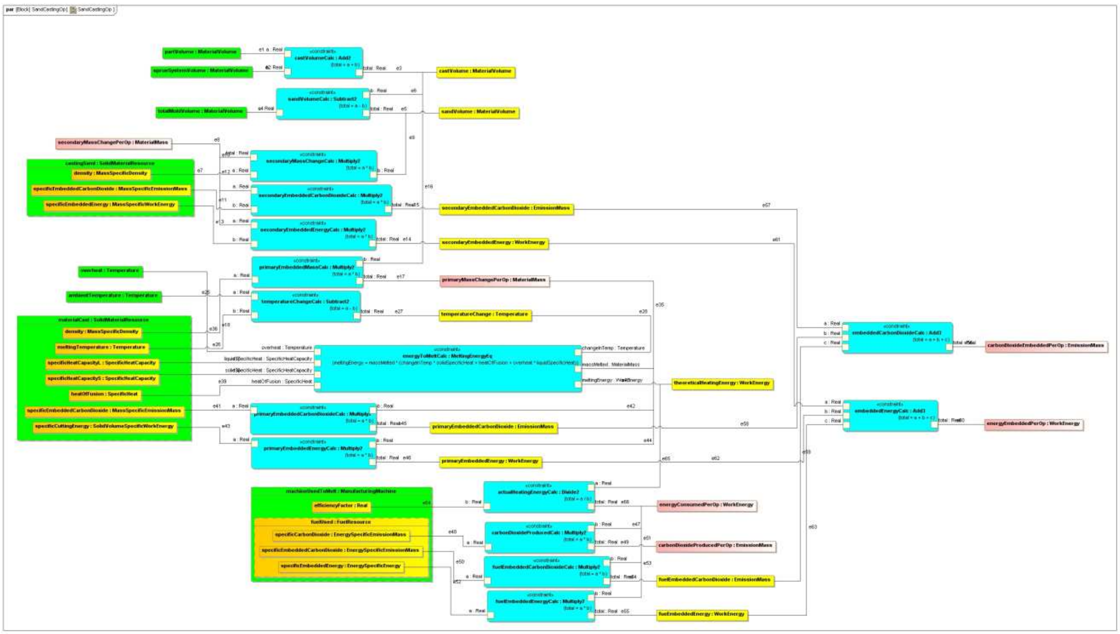

Figure A 2: Sand casting operation parametric diagram

Table A 5: Solvable set of inputs for a sand casting operation

Input	Type/Units
Part Volume	m^3
Sprue System Volume	m^3
Total Mold Volume	m^3
Overheat	K
Ambient Temperature	K
Material Embodied	Material Resource
Casting Sand	Material Resource
Machine Used	Machine Resource

A.4.2 Die Casting Operation

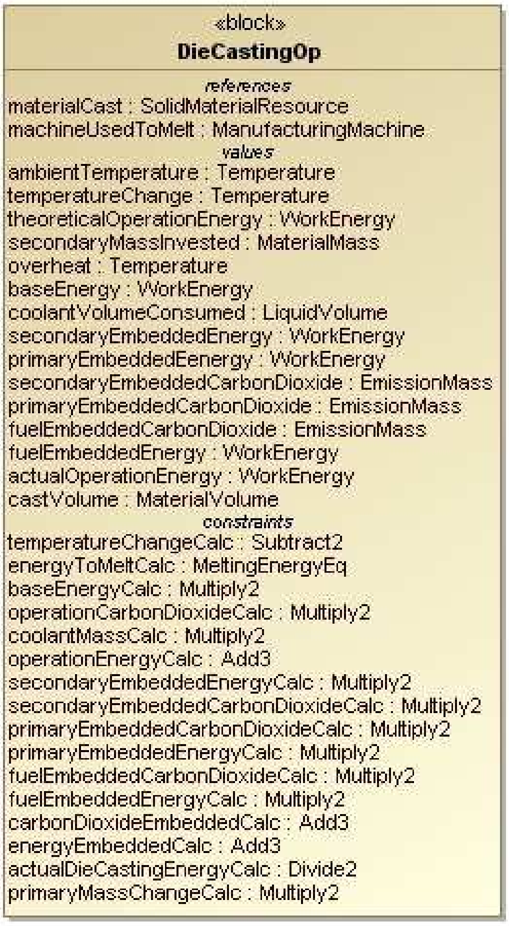

Figure A 3: Die casting operation block

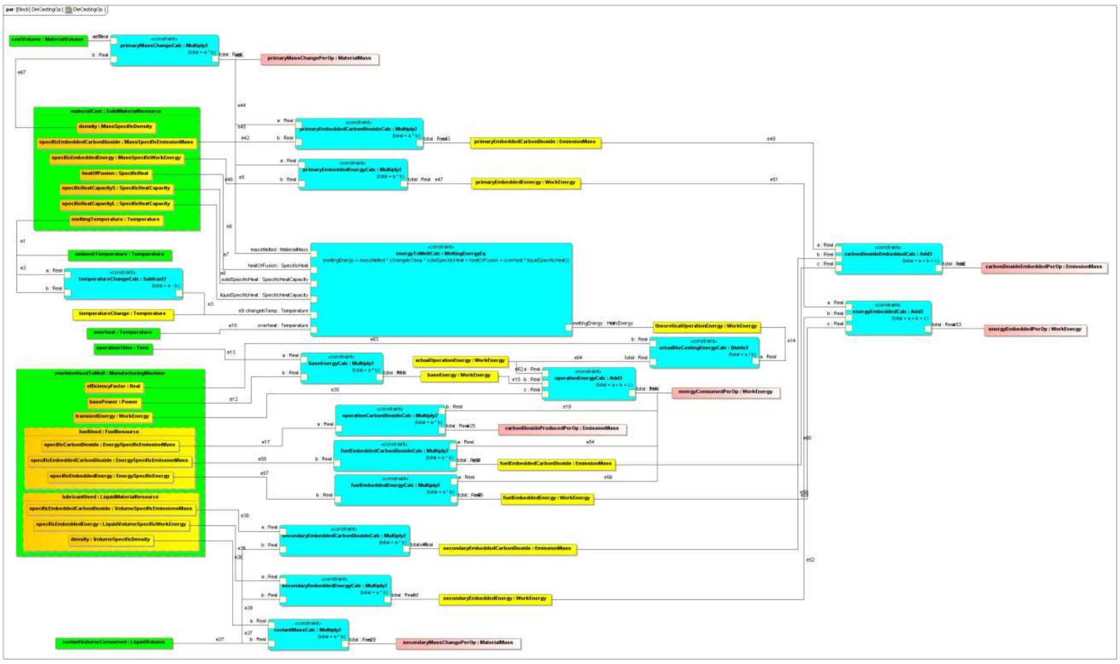

Figure A 4: Die casting operation parametric diagram

Table A 6: Solvable set of inputs for a die casting operation

Input	Type/Units
Cast Volume	m3
Overheat	K
Ambient Temperature	K
Operation Time	s
Coolant Volume Consumed	L
Material Embodied	Material Resource
Machine Used	Machine Resource

A.4.3 Cold Extrusion Operation

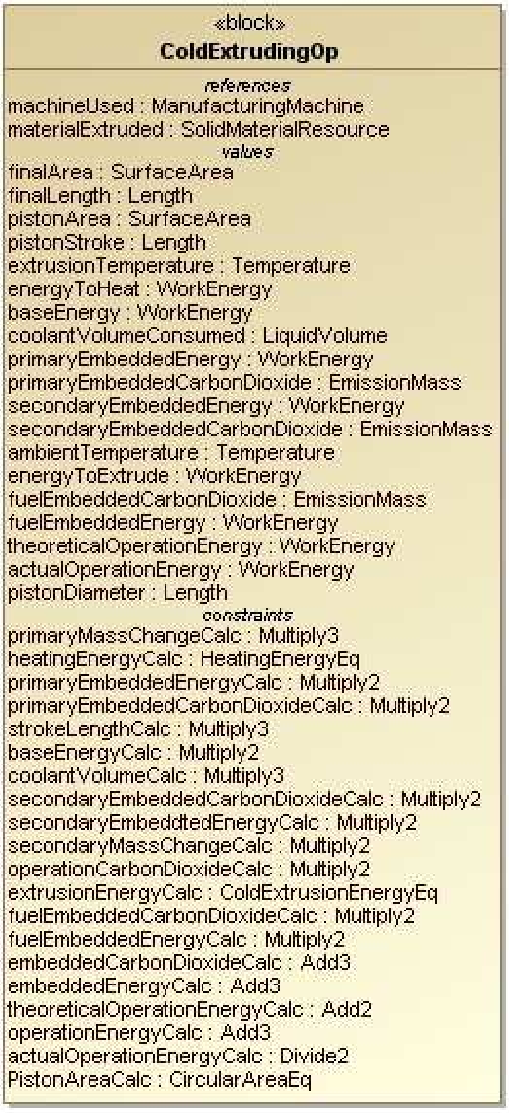

Figure A 5: Cold extrusion operation block

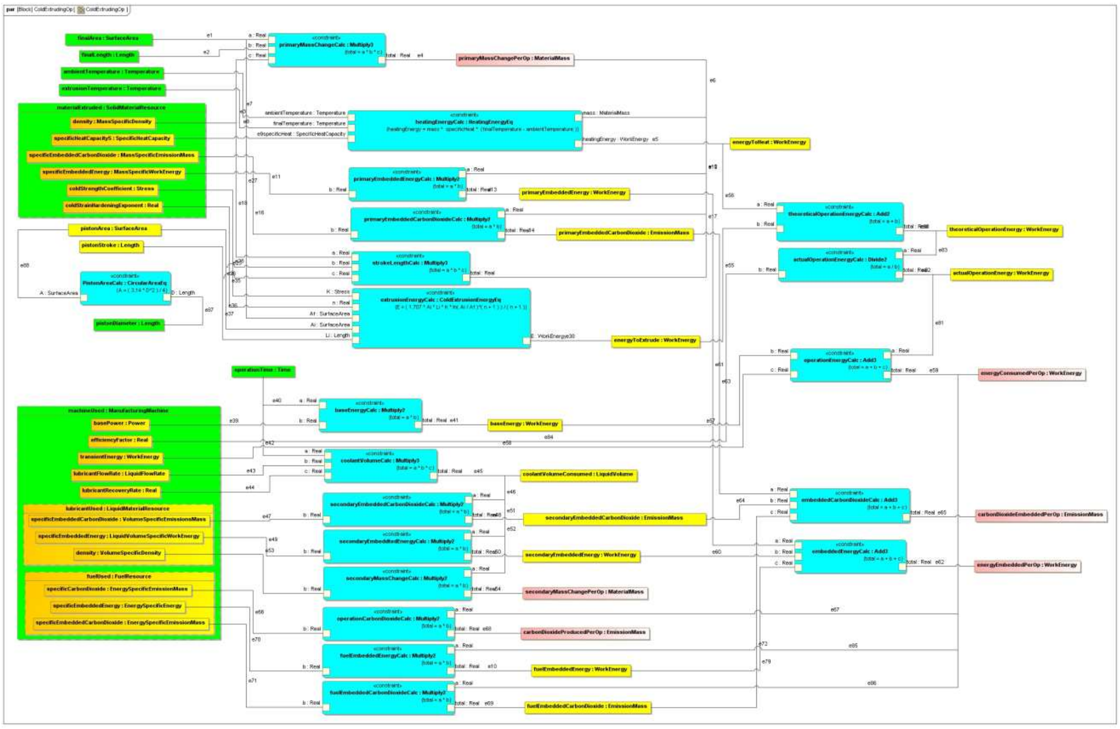

Figure A 6: Cold extrusion operation parametric diagram

Table A 7: Solvable set of inputs for a cold extrusion operation

Input	Type/Units
Final Area	m^2
Final Length	m
Piston Diameter	m
Ambient Temperature	K
Extrusion Temperature	K
Operation Time	s
Material	Material Resource
Machine Used	Machine Resource

A.4.4 Hot Extrusion Operation

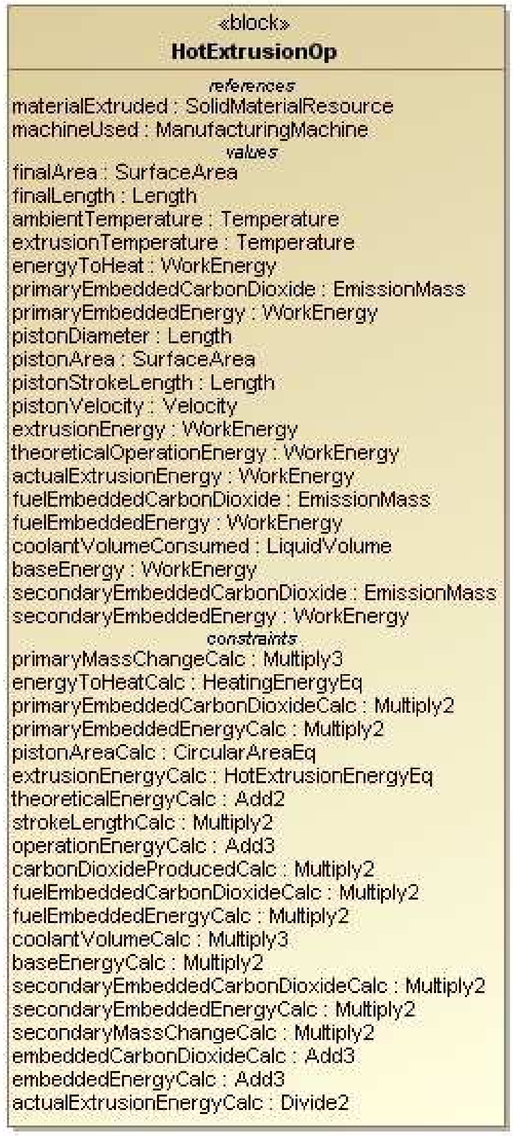

Figure A 7: Hot extrusion operation block

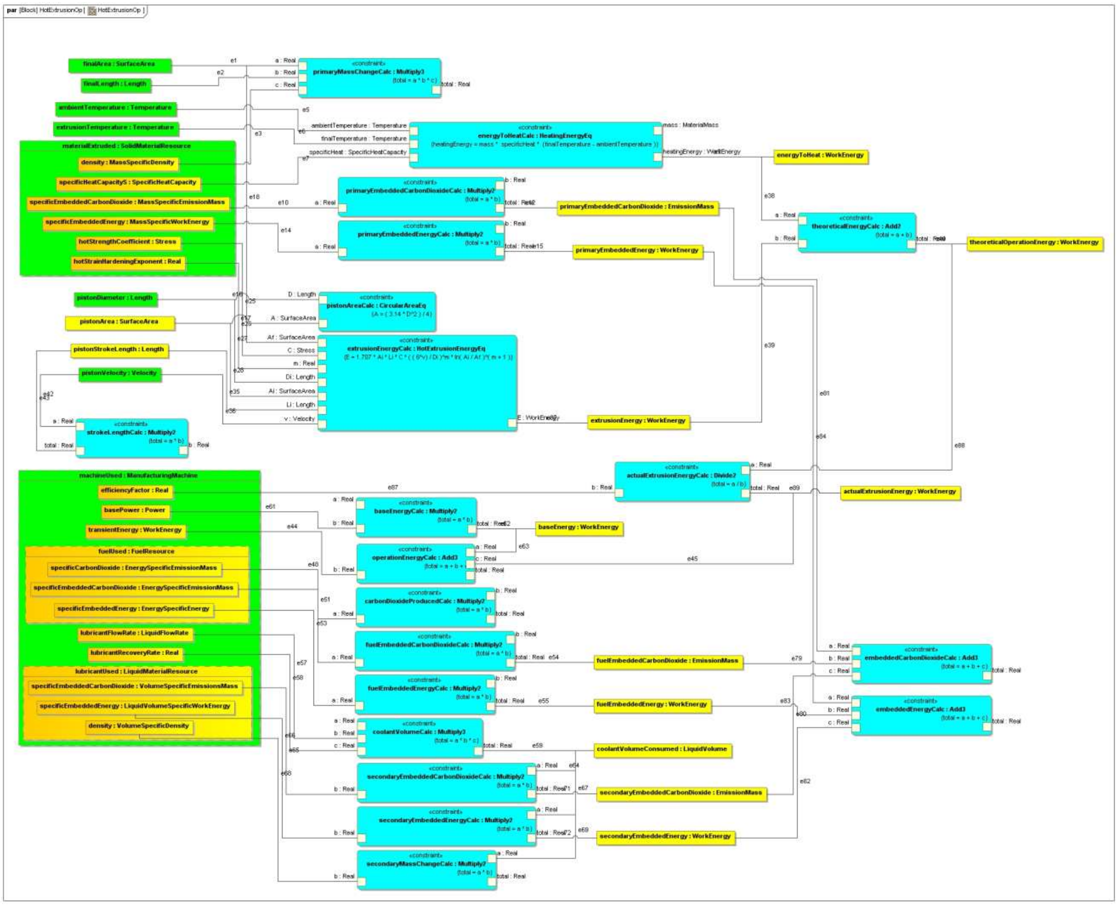

Figure A 8: Hot extrusion operation parametric diagram

Table A 8: Solvable set of inputs for a hot extrusion operation

Input	Type/Units
Final Area	m^2
Final Length	m
Piston Diameter	m
Piston Velocity	m/s
Ambient Temperature	K
Extrusion Temperature	K
Operation Time	s
Material	Material Resource
Machine Used	Machine Resource

A.4.5 Fastening Operation

Figure A 9: Fastening operation block

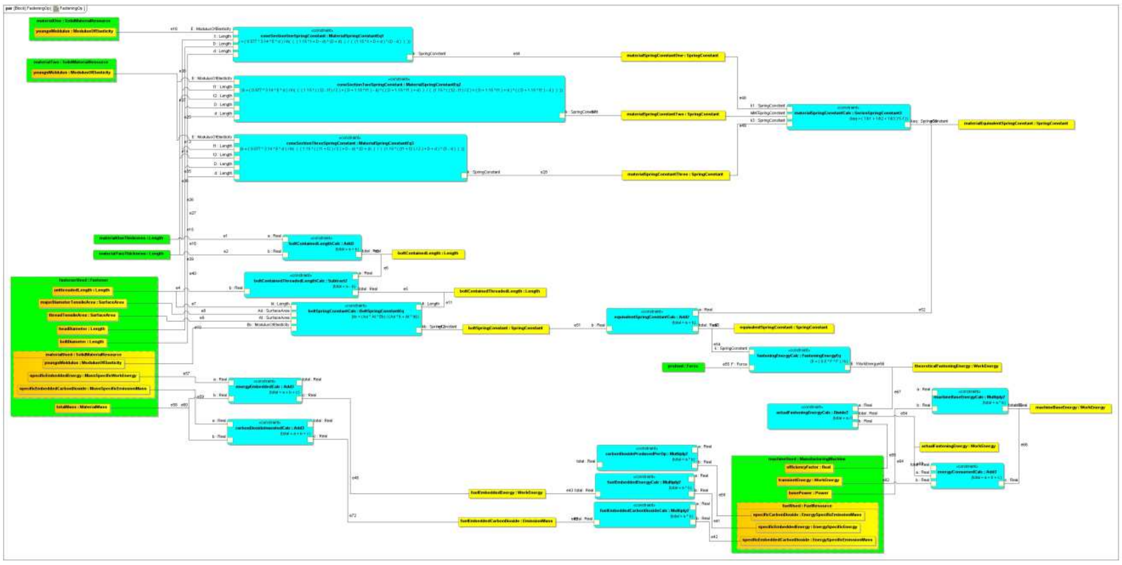

Figure A 10: Fastening operation parametric diagram

Table A 9: Solvable set of inputs for a fastening operation

Input	Type/Units
Material One Thickness	m
Material Two Thickness	m
Operation Time	s
Preload	N
Material One	Material Resource
Material Two	Material Resource
Fastener Used	Fastener Resource
Machine Used	Machine Resource

A.4.6 Cold Rolling Operation

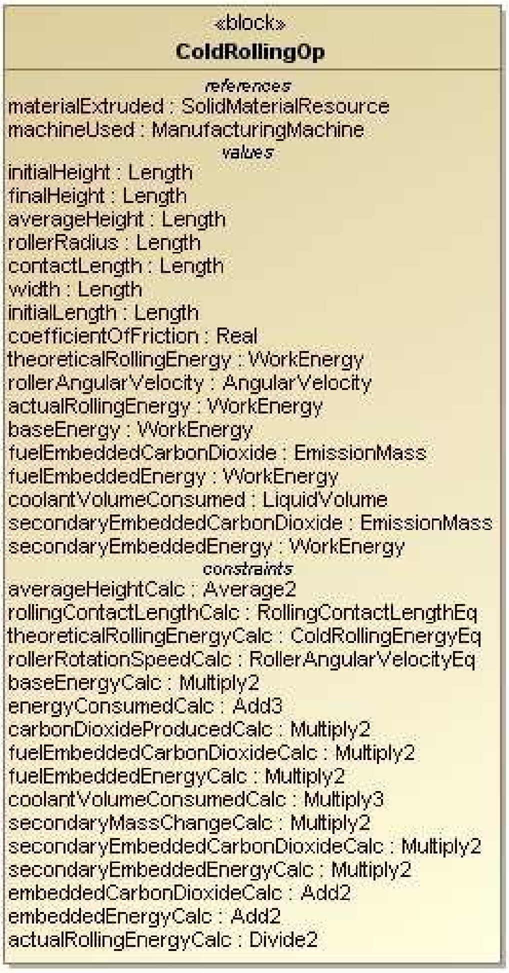

Figure A 11: Cold rolling operation block

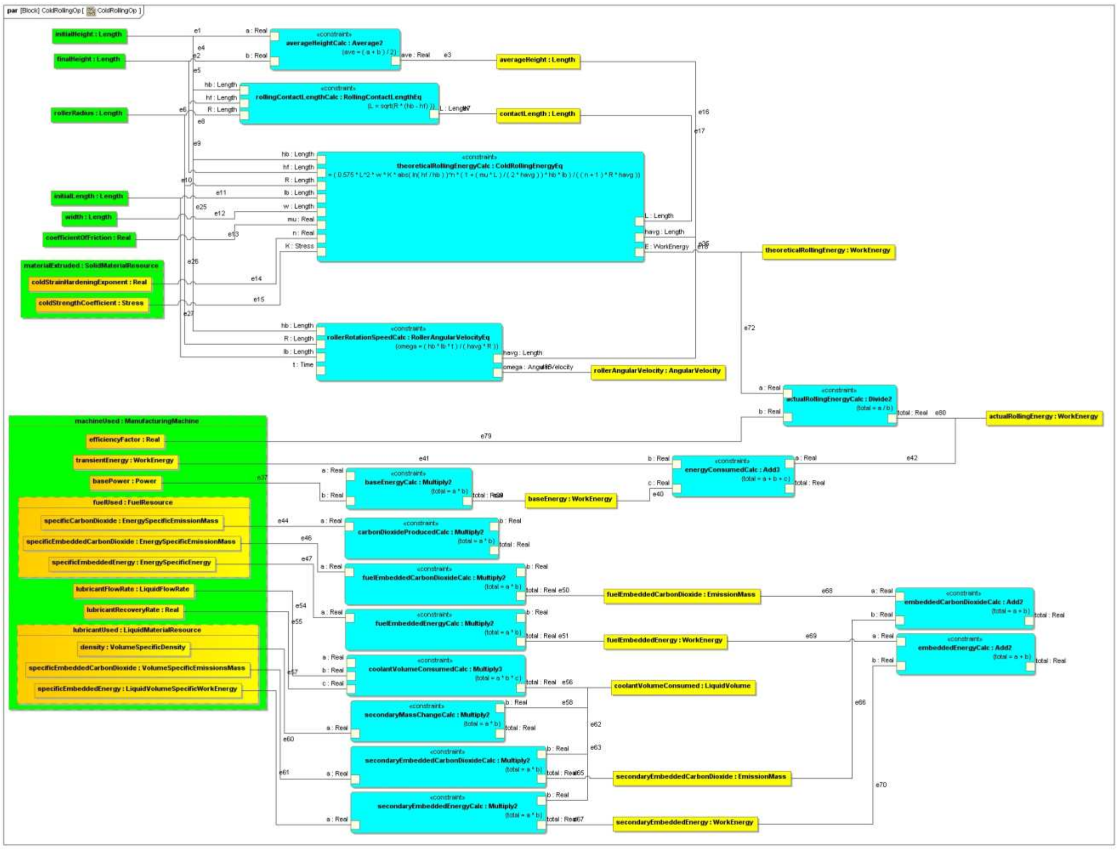

Figure A 12: Cold rolling operation parametric diagram

Table A 10: Solvable set of inputs for a cold rolling operation

Input	Type/Units
Initial Height	m
Final Height	m
Roller Radius	m
Initial Length	m
Width	m
Coefficient of Friction	unitless
Operation Time	s
Material	Material Resource
Machine Used	Machine Resource

A.4.7 Sheet Metal Bending Operation

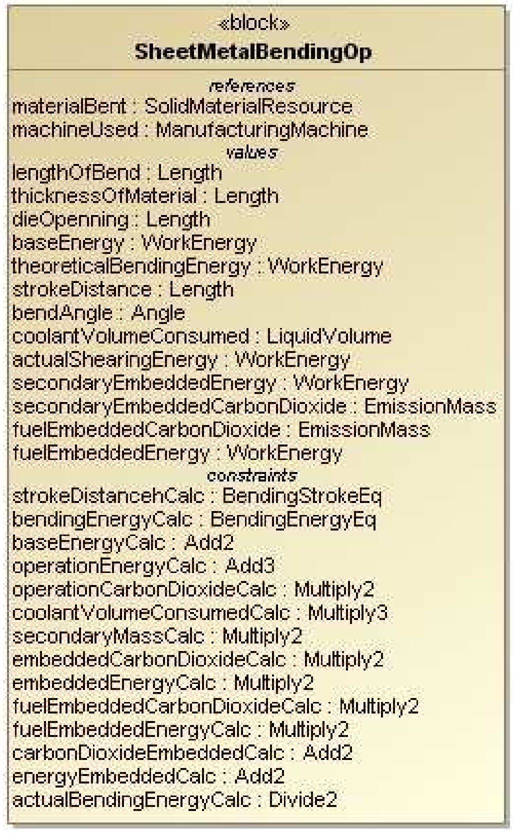

Figure A 13: Sheet metal bending operation block

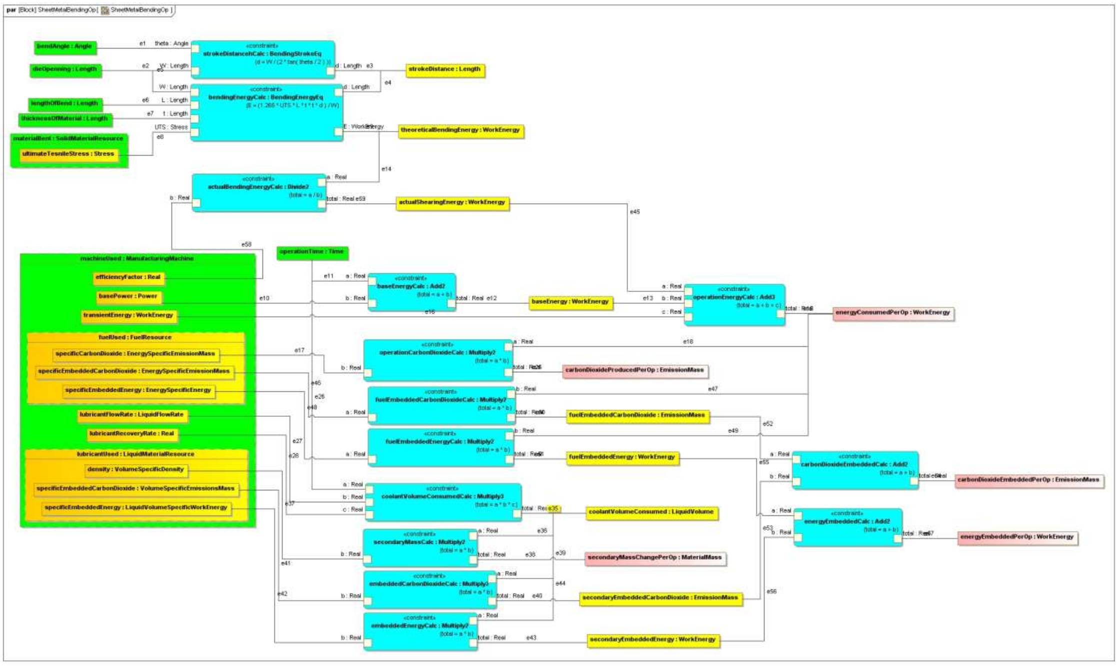

Figure A 14: Sheet metal bending operation parametric diagram

Table A 11: Solvable set of inputs for a sheet metal bending operation

Input	Type/Units
Bend Angle	rad
Die Openning	m
Length of Bend	m
Thickness of Material	m
Operation Time	s
Material	Material Resource
Machine Used	Machine Resource

A.4.8 Shearing Operation

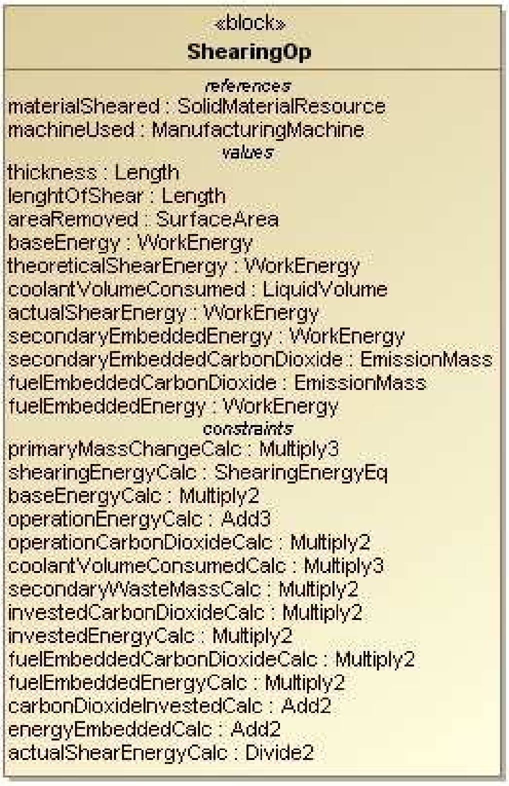

Figure A 15: Shearing operation block

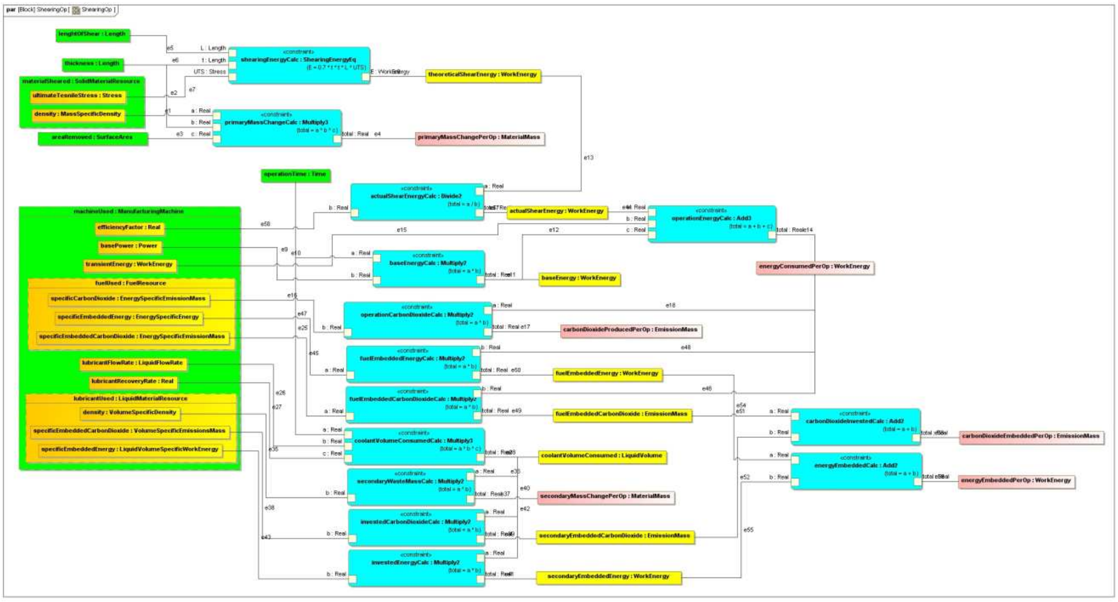

Figure A 16: Shearing operation parametric diagram

Table A 12: Solvable set of inputs for a shearing operation

Input	Type/Units
Length of Sheared Edge	m
Material Thickness	m
Area Removed	m^2
Operation Time	s
Material	Material Resource
Machine Used	Machine Resource

A.4.9 Sawing Operation

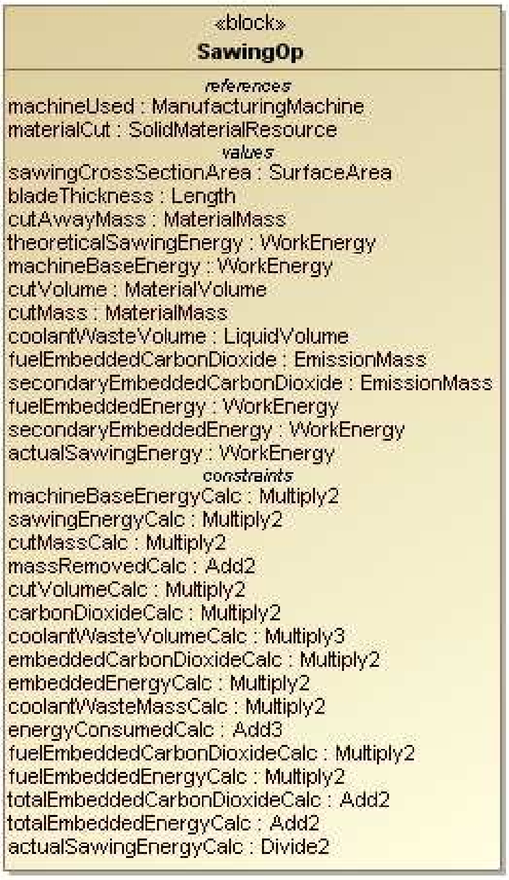

Figure A 17: Sawing operation block

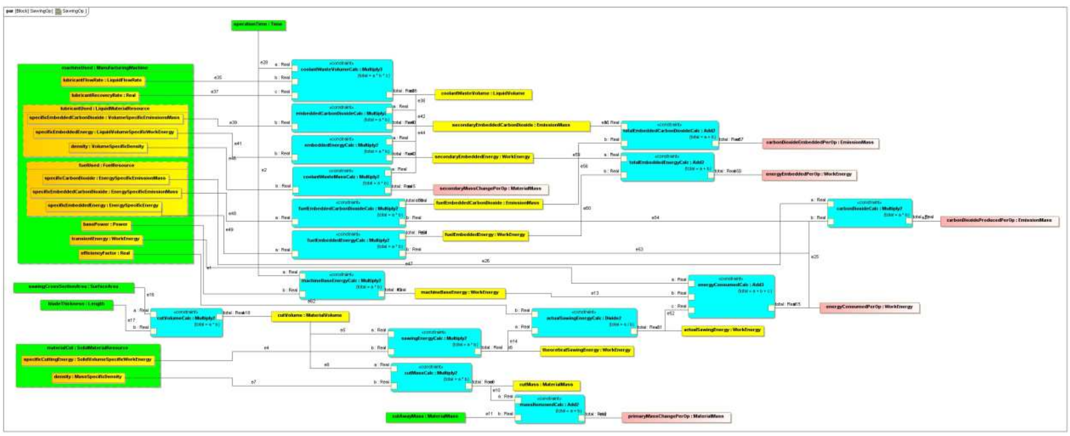

Figure A 18: Sawing operation parametric diagram

Table A 13: Solvable set of inputs for a sawing operation

Input	Type/Units
Blade Thickness	m
Cutting Cross Sectional Area	m^2
Cut Away Mass	kg
Operation Time	s
Material	Material Resource
Machine Used	Machine Resource

A.4.10 Machining Operation

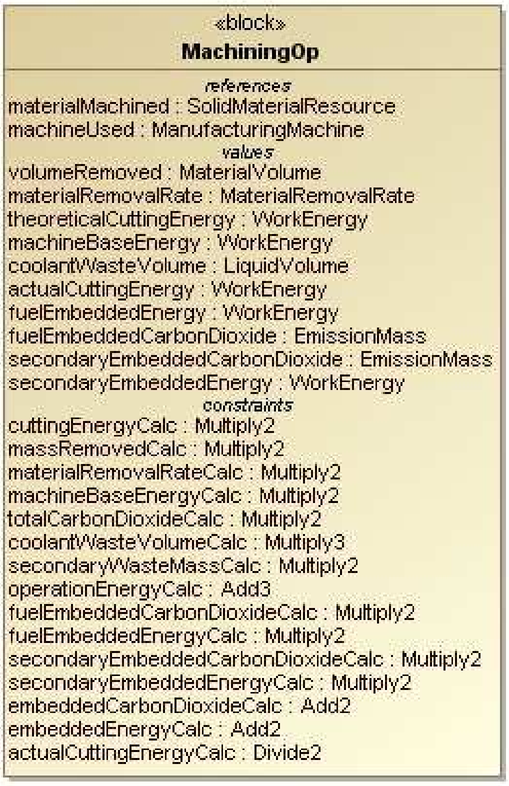

Figure A 19: Machining operation block

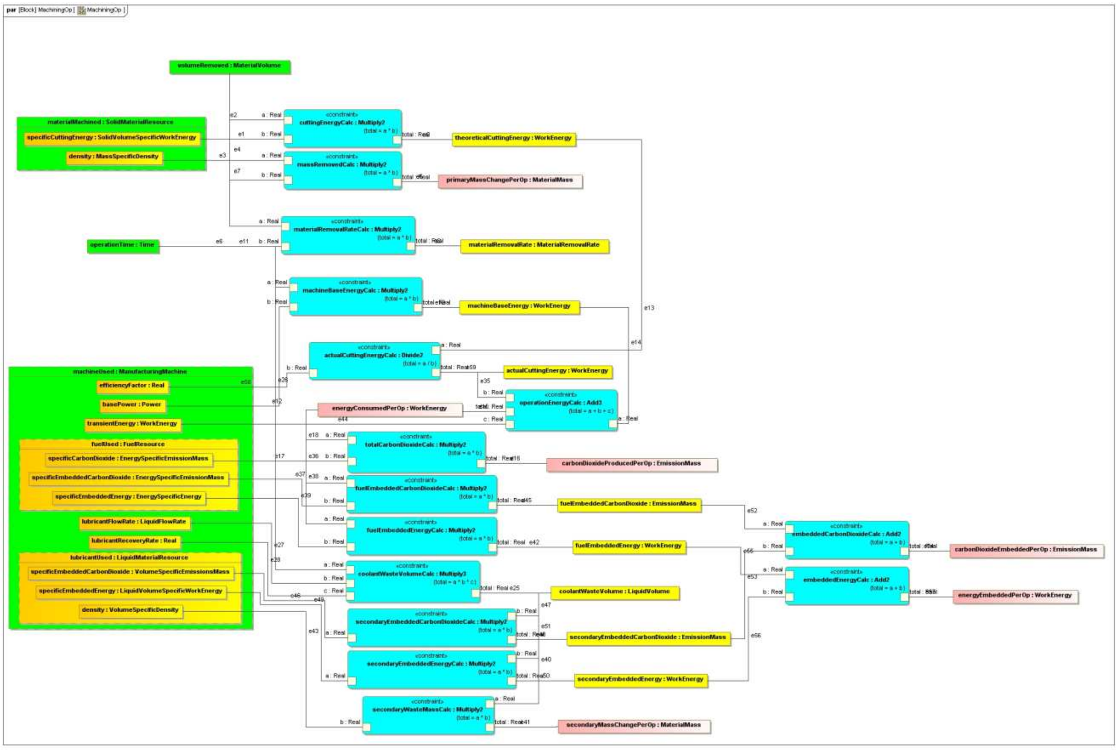

Figure A 20: Machining operation parametric diagram

Table A 14: Solvable set of inputs for a machining operation

Input	Type/Units
Volume Removed	m^3
Material Removal Rate	m^3/s
Material	Material Resource
Machine Used	Machine Resource

Appendix B: Case Study Instance Blocks

B.1 Cast Wing Instances

Figure A 21: Cast wing spar operations

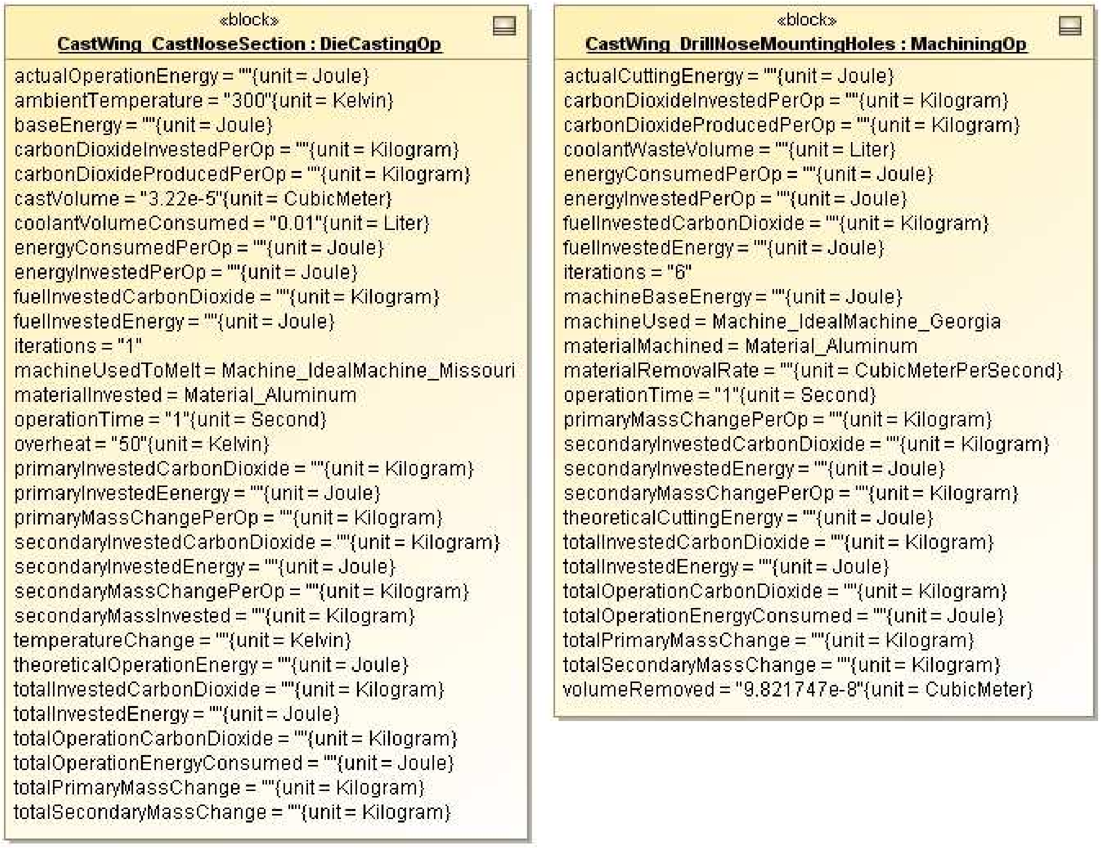

Figure A 22: Cast wing rib nose section operations

Figure A 23: Cast wing rib tail section operations

Figure A 24: Cast wing joining operations

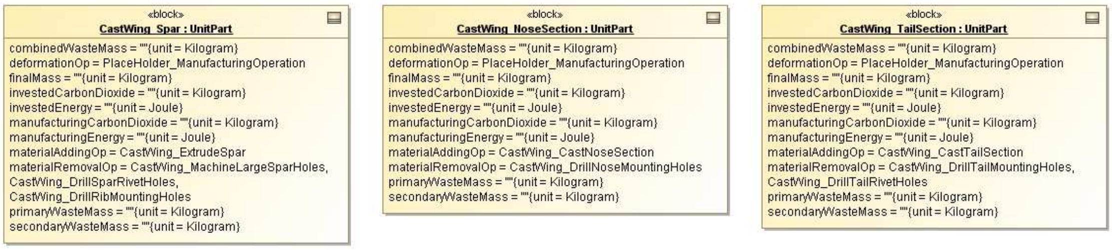

Figure A 25: Cast wing unit parts

Figure A 26: Cast wing assembly

Figure A 27: Cast wing fabrication plant and processes

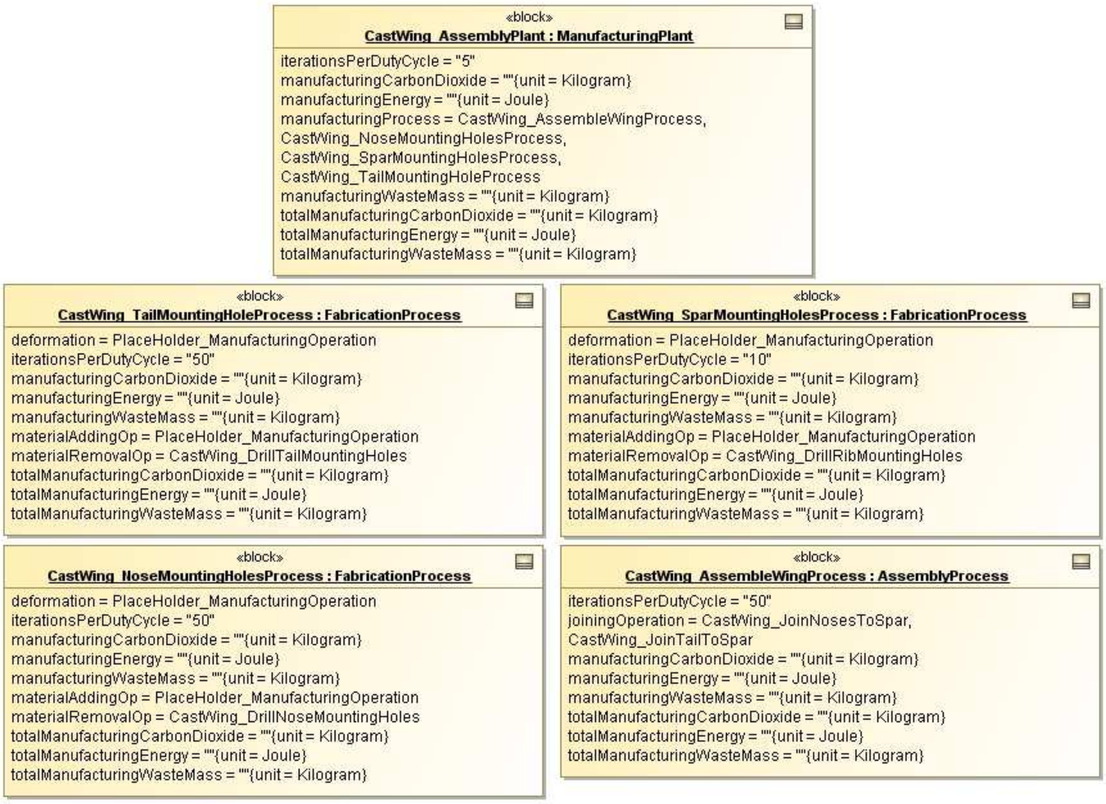

Figure A 28: Cast wing assembly plant and processes

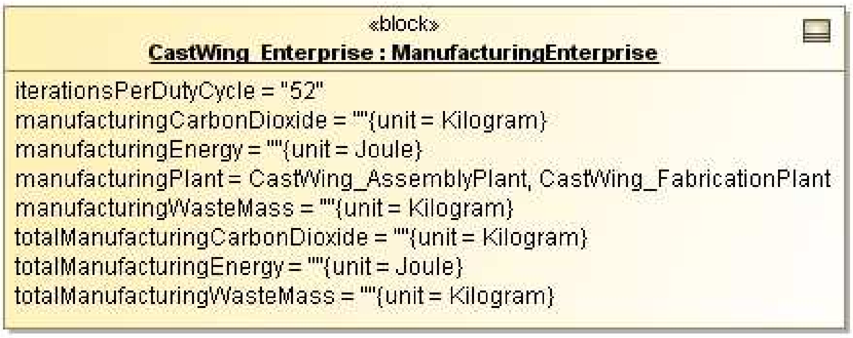

Figure A 29: Cast wing enterprise

B.2 Sheet Metal Wing Instances

Figure A 30: Sheet metal wing spar operations

Figure A 31: Cast wing spar stabilizer operations

Figure A 32: Sheet metal wing rib nose operations

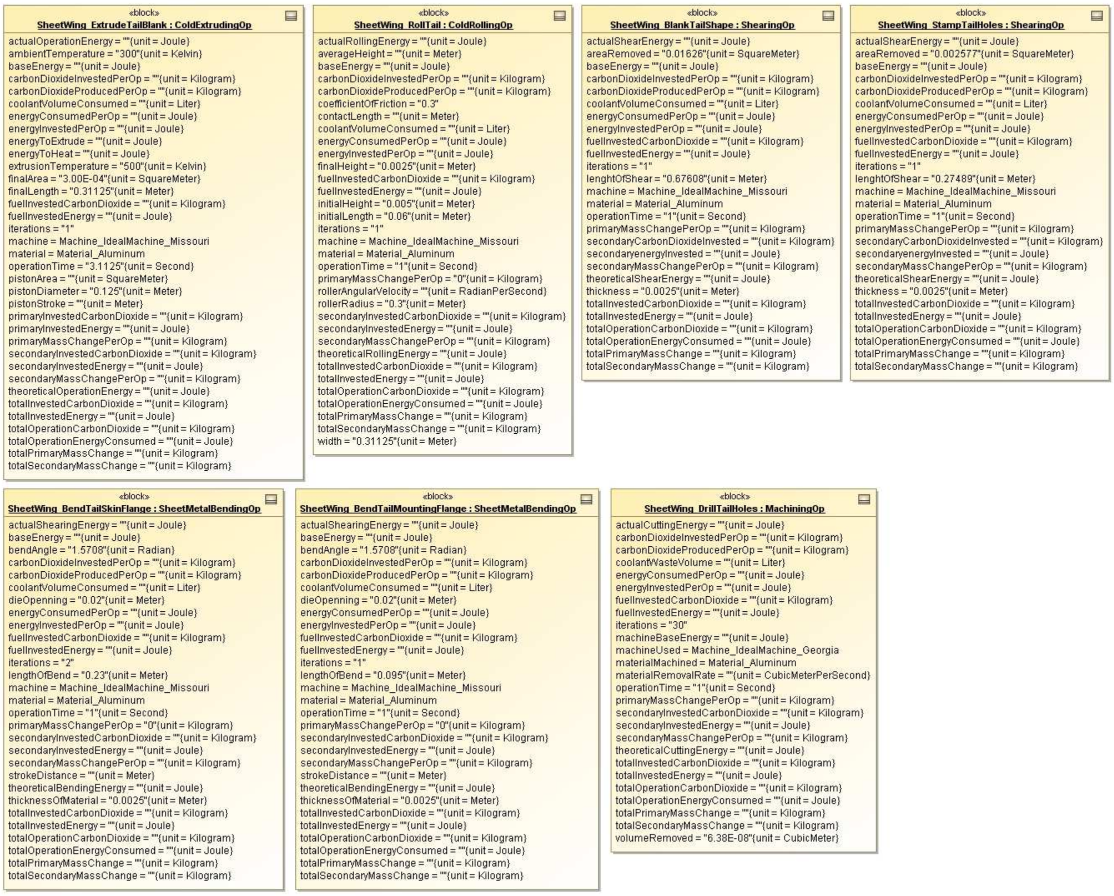

Figure A 33: Sheet metal wing rib tail operations

Figure A 34: Sheet metal wing joining operations

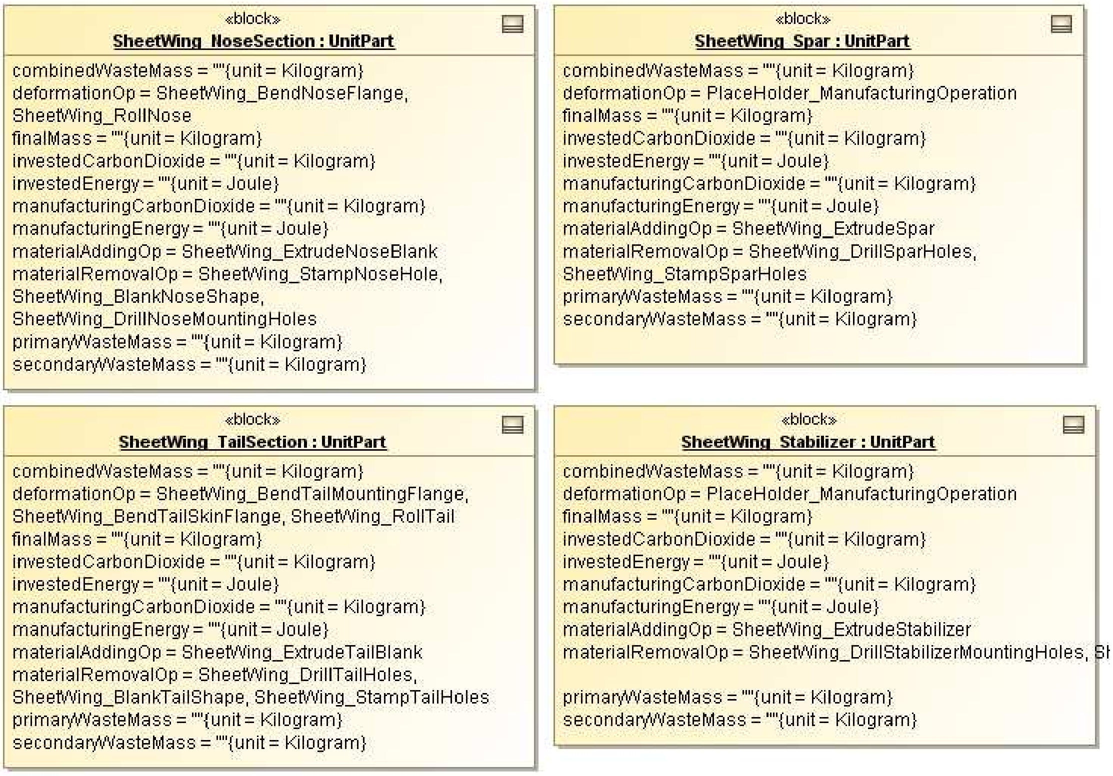

Figure A 35: Sheet metal wing unit parts

Figure A 36: Sheet metal wing assembly

Appendix C: Part CAD Drafts

C.1 Validation Experiment

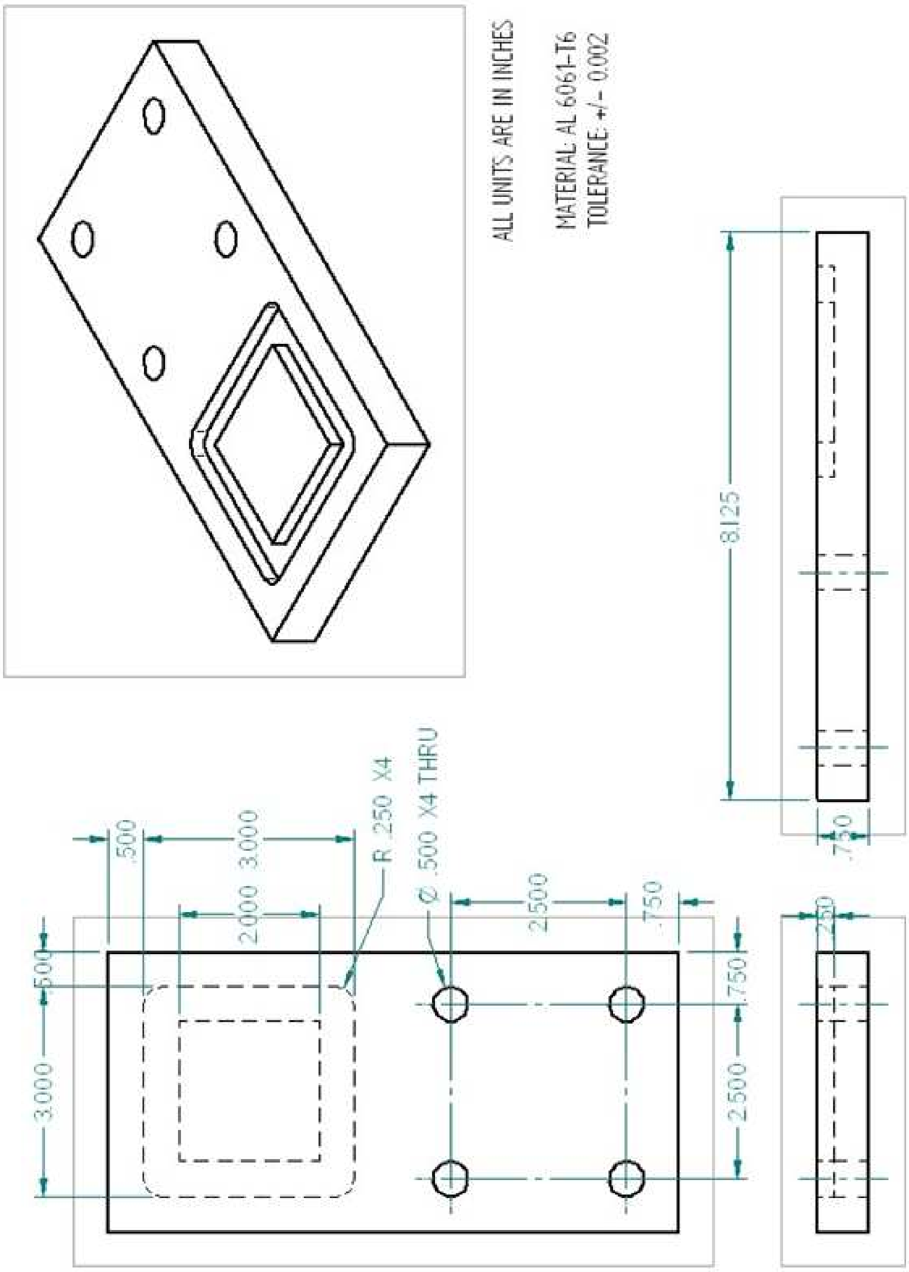

Figure A 37: Validation experiment part

C.2 Cast Wing

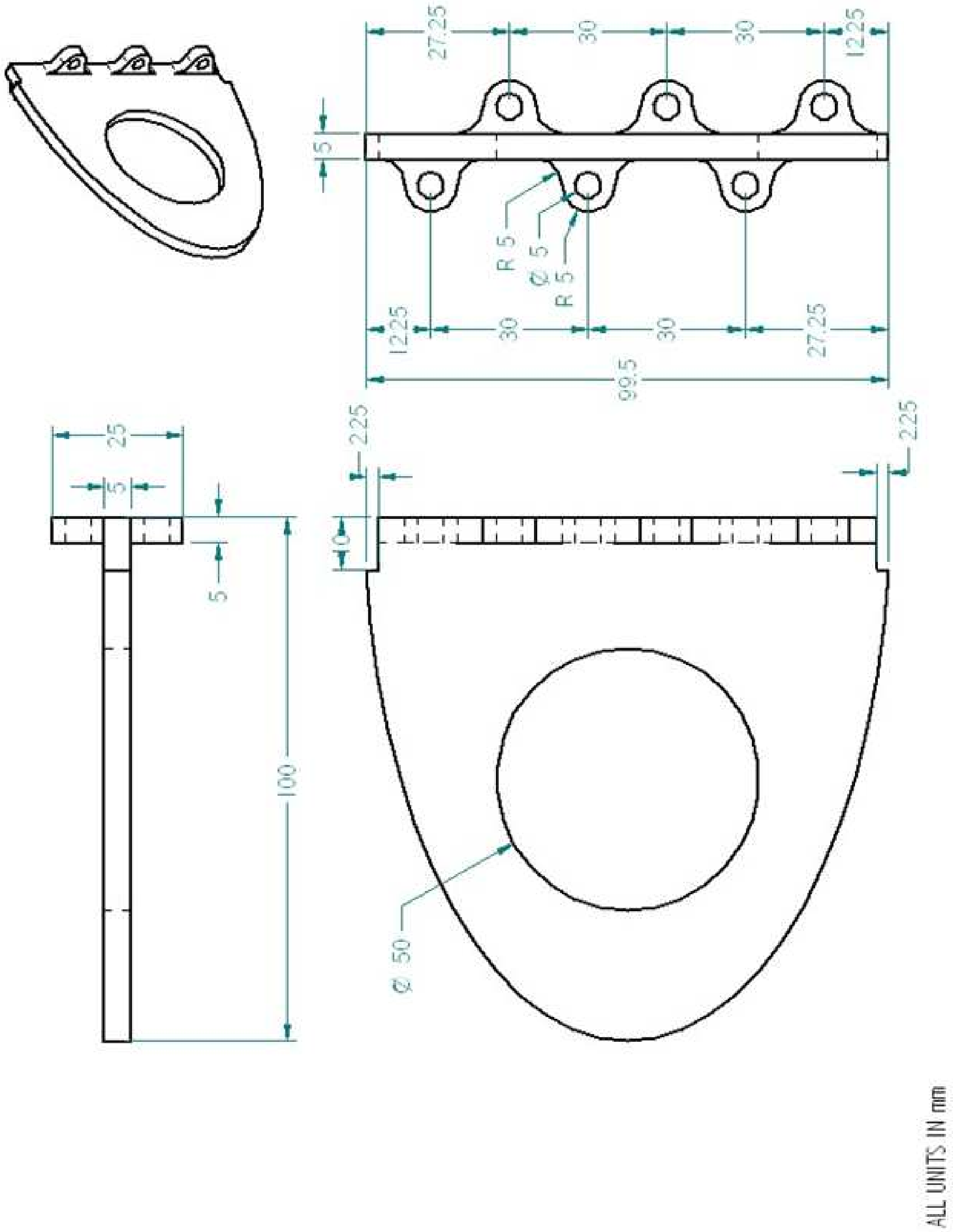

Figure A 38: Cast wing rib nose section

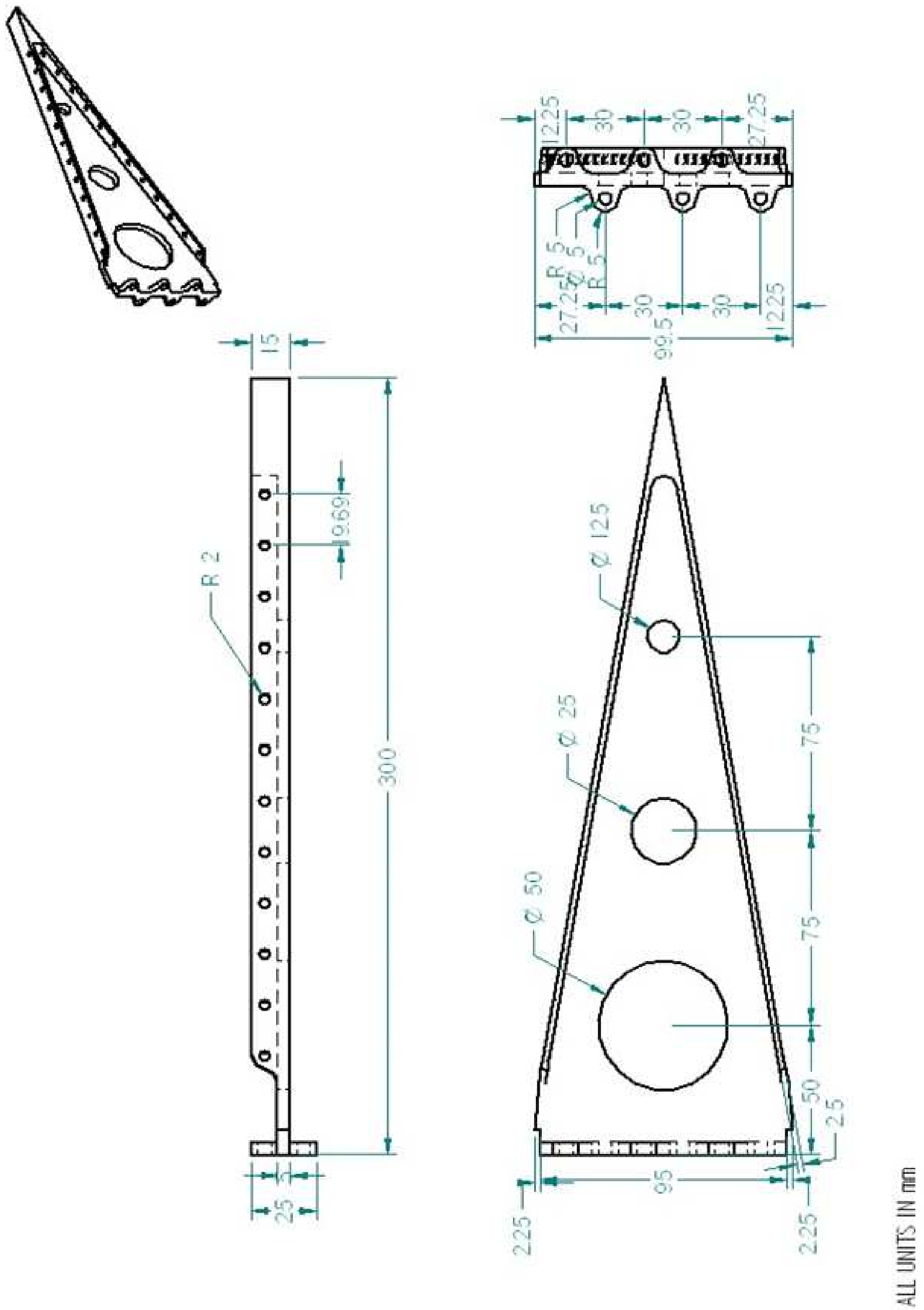

Figure A 39: Cast wing rib tail section

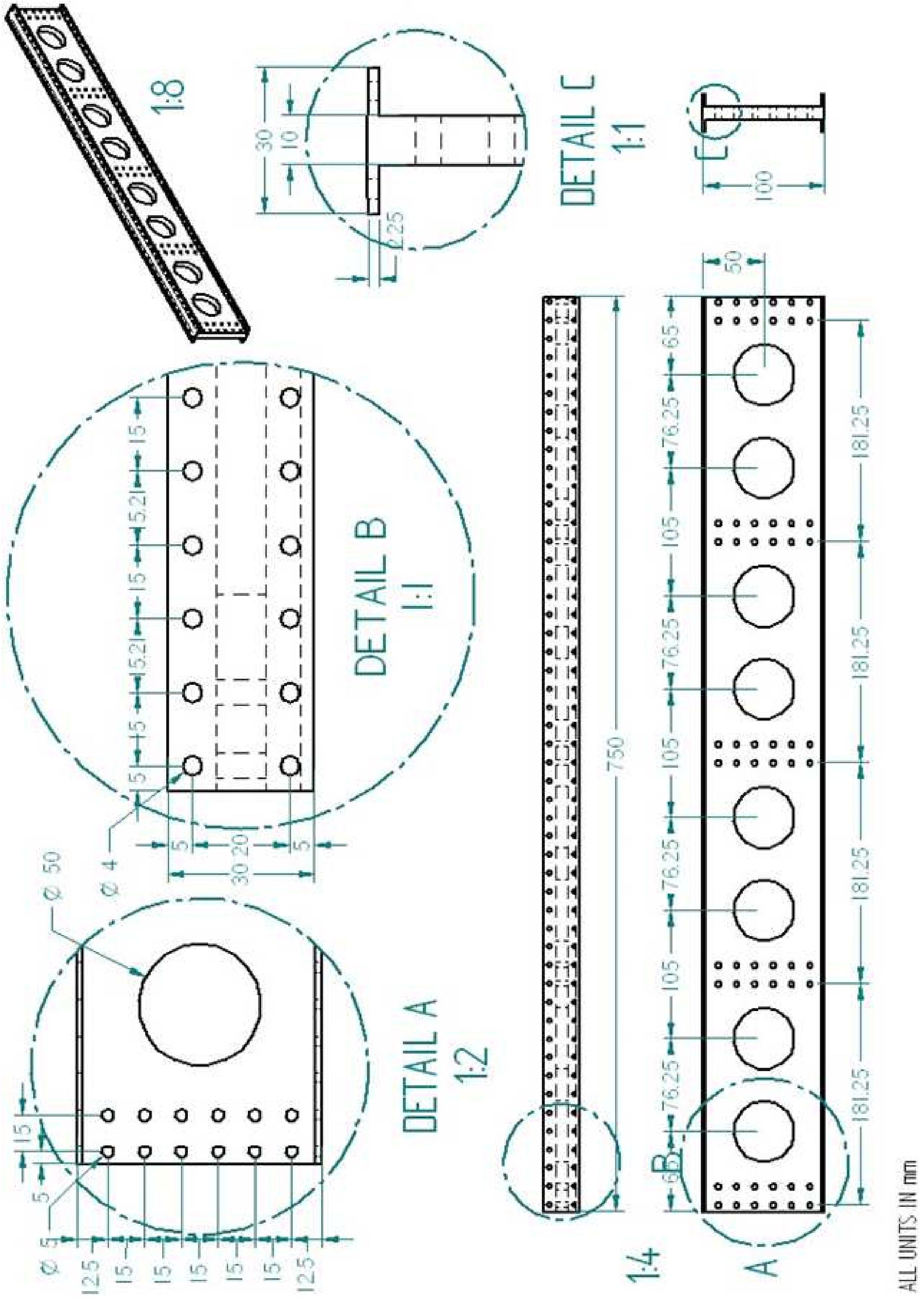

Figure A 40: Cast wing spar

C.3 Sheet Metal Wing

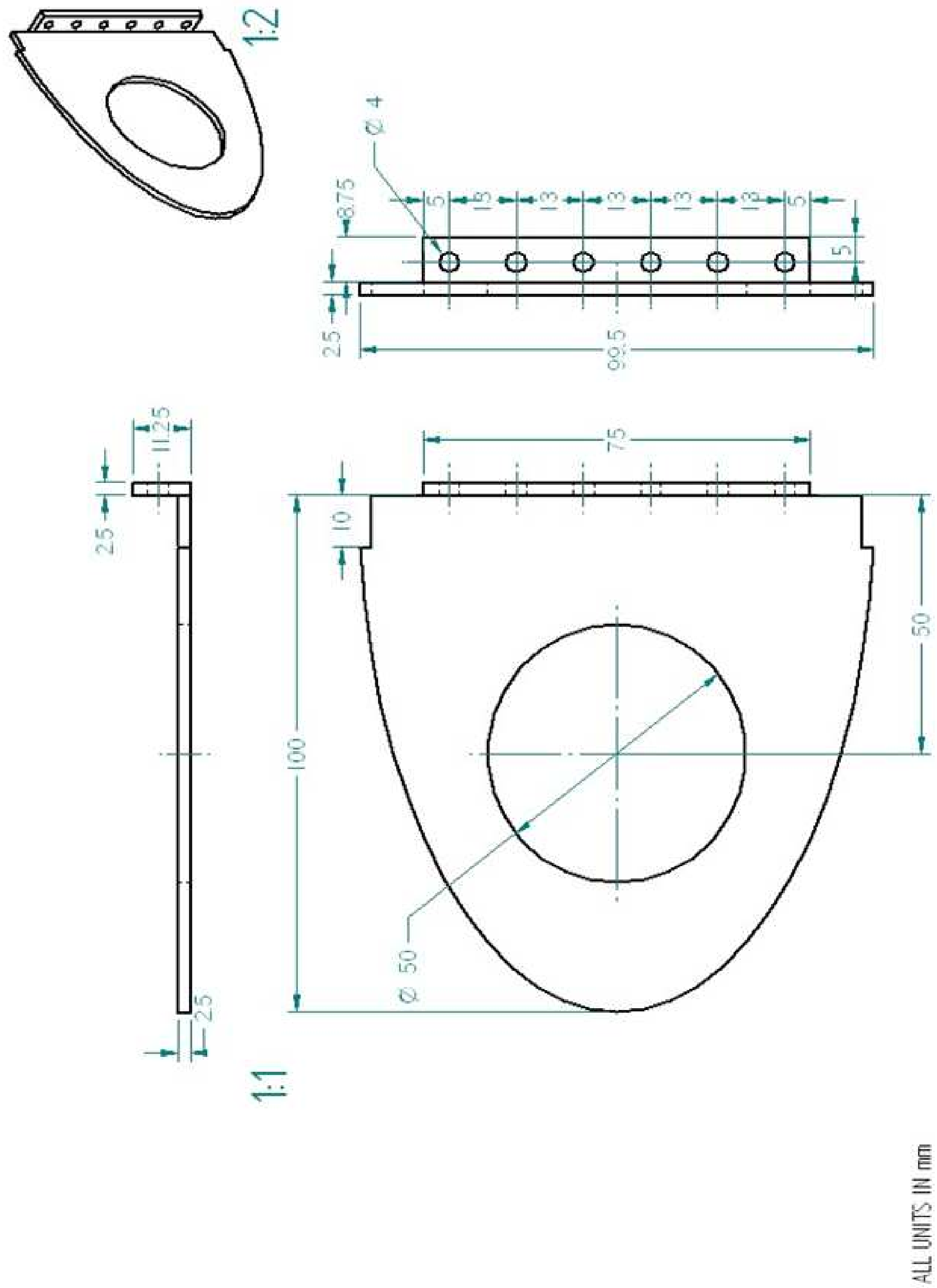

Figure A 41: Sheet metal wing rib nose

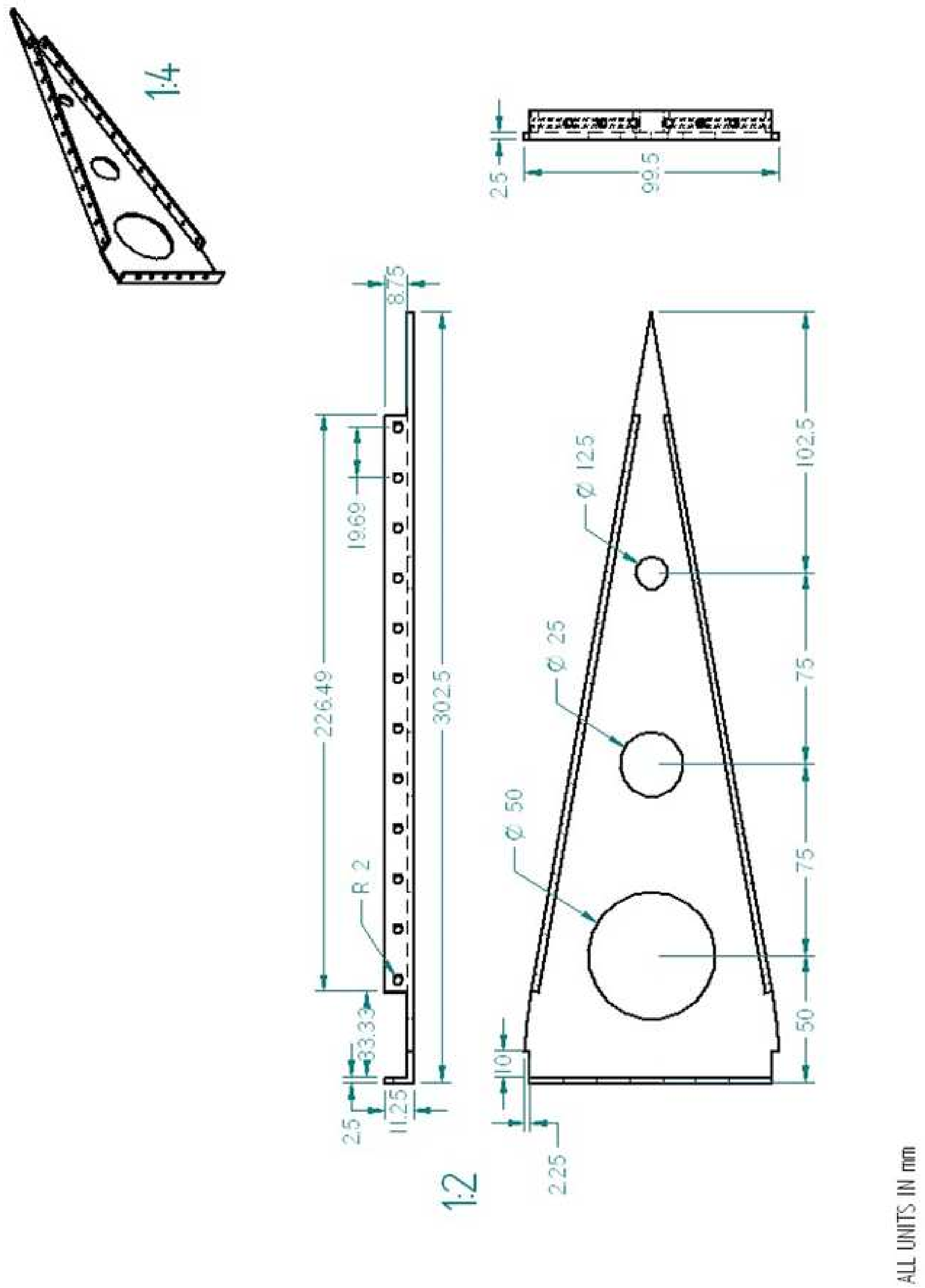

Figure A 42: Sheet metal wing rib tail

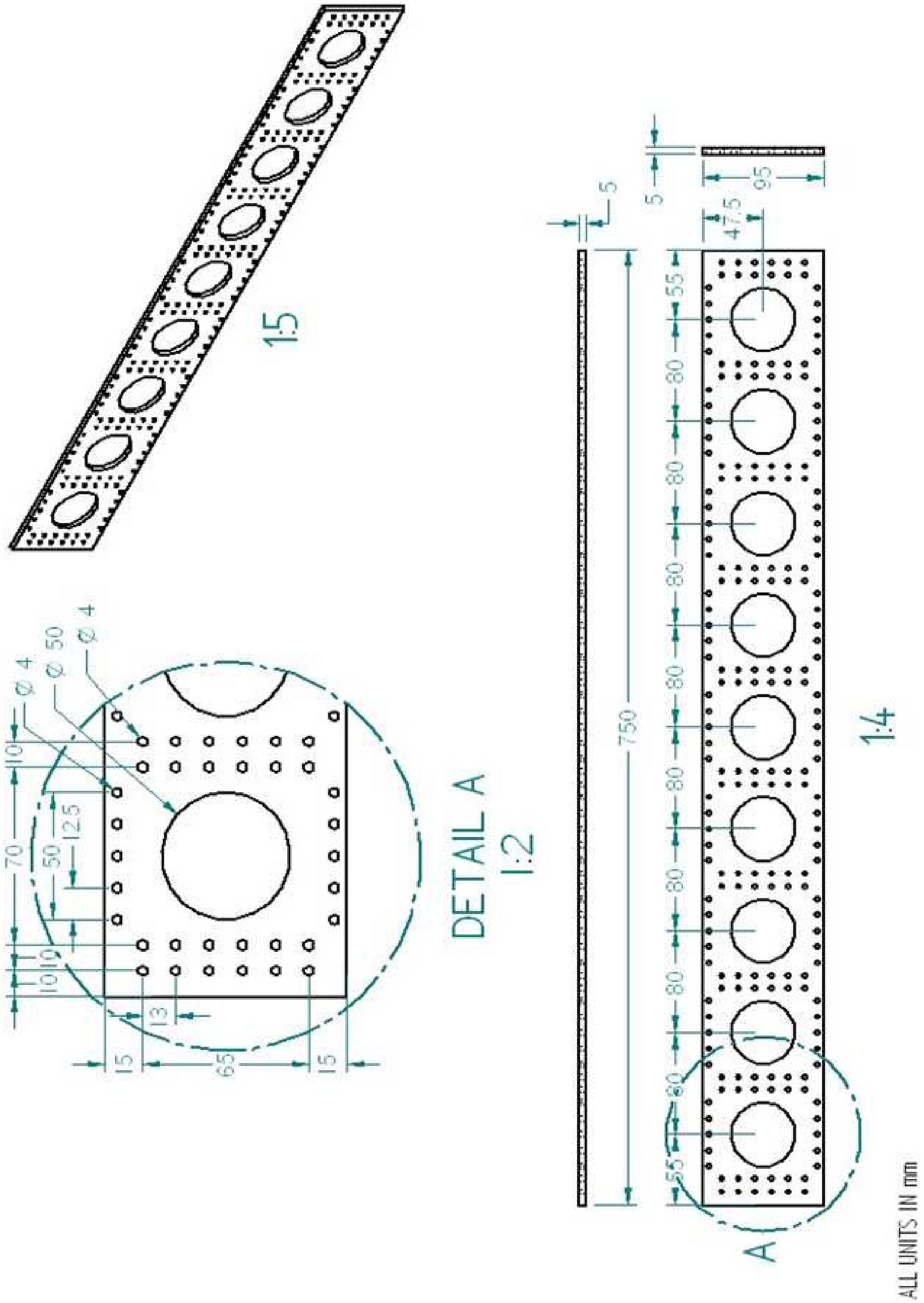

Figure A 43: Sheet metal wing spar

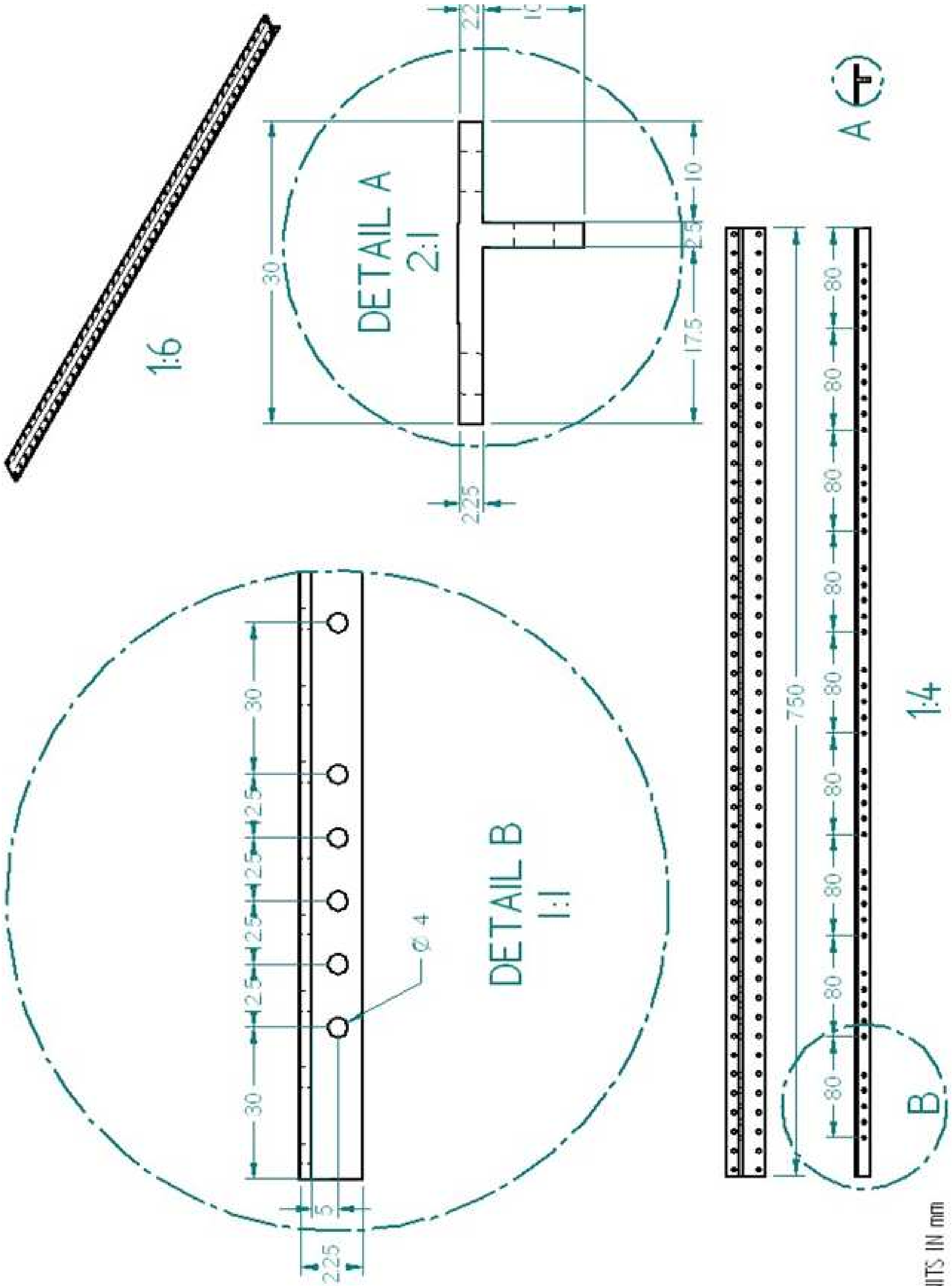

Figure A 44: Sheet metal wing spar stabilizer

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