AN INVESTIGATION INTO THE IMPLEMENTATION OF MULTI-OBJECTIVE OPTIMIZATION IN SUSTAINABLE MANUFACTURING:

A CASE STUDY FROM HOUSEHOLD GOODS INDUSTRY

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ABSTRACT

AN INVESTIGATION INTO THE IMPLEMENTATION OF MULTI OBJECTIVE OPTIMIZATION IN SUSTAINABLE MANUFACTURING: A CASE STUDY FROM HOUSEHOLD GOODS INDUSTRY

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Sustainable manufacturing is defined as the creation of goods and services using processes that minimize negative environmental impacts, conserve energy, e.t.c. It is important for a manufacturing firm to measure and assess environmental impact along with three different dimensions: enterprise, process and product.

Every enterprise needs to track and asses its environmental impact for accountability reasons towards its consumers, employees, society and government. It is known that immeasurable things cannot be managed in the environmental systems.

The Refrigerator Compressor Plant is one of the manufacturing firms that come across emission problem existing due to energy consumption. It is known that there is a direct relation between energy consumption and carbon emissions. In other words, energy optimization is a key to reduce carbon emissions. Therefore, energy optimization studies are made in this Plant.

This research mainly focuses on modeling and simulation of a sustainable manufacturing system by the use of a crankshaft production line and optimization of auxiliary energy consumption per part, overall cost per part, and number of finished parts per shift of The Refrigerator Compressor Plant.

Thesis study starts with the production line examination and data acquisition. Then, System model is prepared and run in Arena software using real data. For optimization study, Simulation model variables are used as inputs. Simulation model is used with integration of optimization solver, OptQuest. Finally, simulation-based multi objective optimization process is completed.

Keywords: Sustainable Manufacturing, Modeling, Simulation-based Multi Objective Optimization, Arena®, OptQuest

ÖZ

SÜRDÜRÜLEBİLİR ÜRETİMDE ÇOKLU AMAÇ OPTİMİZASYON UYGULAMASININ ARAŞTIRILMASI: EV EŞYALARI ENDÜSTRİSİ İLE İLGİLİ VAKA ÇALIŞMASI

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Sürdürülebilir üretim, negatif çevresel etkileri minimize eden, enerjiyi koruyan vb. prosesleri kullanarak mal ve hizmet oluşturulması olarak tanımlanır. Üretim firmaları için üç farklı boyutla, kurum, işlem ve üretim, çevresel etkiyi ölçmek ve değerlendirmek önemlidir.

Her kurum tüketicileri, çalışanları, toplum ve hükümete doğru hesapverebilirlik sebepleri için çevresel etkinin takip edilmesi ve değerlendirilmesine ihtiyaç duyar. Çevresel sistemlerde ölçülemeyen şeylerin yönetilemediği bilinmektedir.

Buzdolabı kompresör işletmesi enerji tüketimi nedeniyle ortaya çıkan emisyon problemiyle karşılaşan üretim firmalarından biridir. Enerji tüketimi ile karbon emisyonu arasında doğrudan bir ilişki olduğu bilinmektedir. Diğer bir değişle, enerji optimizasyonu karbon emisyonlarını azaltmak için bir anahtardır. Bundan dolayı, enerji optimizasyonu çalışmaları bu işletmede yapılmaktadır.

Bu araştırma temel olarak krank üretim hattı kullanılarak ve Buzdolabı Kompresör İşletmesi'nin parça başına yardımcı enerji tüketiminin, parça başına toplam maliyetinin ve vardiya başına bitmiş parçaların sayısının optimizasyonu yapılarak, sürdürülebilir üretim sisteminin modellenmesi ve simulasyonuna odaklanmaktadır.

Tez çalışması, üretim hattının değerlendirilmesi ve very sağlanmasıyla başlamaktadır. Sonra, sistem modeli gerçek veri kullanan Arena yazılımında oluşturulmakta ve çalıştırılmaktadır. Optimizasyon çalışması için, simulasyon model değişkenleri girdiler olarak kullanılmaktadır. Simulasyon modeli optimizasyon çözücü, OptQuest, ile entegre bir şekilde kullanılmaktadır. En sonunda, simulasyon-tabanlı çoklu amaç optimizasyon işlemi tamamlanmaktadır.

Anahtar Kelimeler: Sürdürülebilir Üretim, Modelleme, Simulasyon-tabanlı Çoklu Amaç Optimizasyonu, Arena®, OptQuest

To My Parents

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CHAPTER 1

INTRODUCTION

In recent years, as the global depletion, environmental pollution and climate change get worse because of increasing global industrialization, manufacturing industries are under pressure to cope with the problems and sustain competitiveness (Feng et al., 2009). Therefore, nowadays, energy conservation, carbon reduction, cost minimization and pollutant emissions reduction are of the biggest challenges to governments, professionals and society (Lu et al., 2015).

Manufacturing industries' efforts to improve environmental performance such as decreasing carbon emissions and energy consumption have moved towards thinking in terms of life cycles and environmental strategies and management systems (OECD, 2009). Therefore, final good life cycle has been investigated for determining environmental impacts in detail. As a result of the investigation, in The Refrigerator Compressor Plant, manufacturing process of Type-A crankshaft has been focused on. In order to cope with the multiple objectives in the existing system such as minimization of auxiliary energy consumption and overall cost per part per shift, and maximization of the number of finished products per shift, multi objective optimization process has been investigated in detail.

In multi objective optimization studies, qualified person (Zhou et al., 2013) tries to optimize his/her decision in terms of conflicting objectives. In that point, he/she tries to identify the best decision tradeoff between the manufacturing system and benefit of green improvement.

In this Thesis, there are no conflicting objectives that should be considered. That means improving performance on one objective does not deteriorate performance of one or more other objectives.

Nowadays, implementing changes within the existing system are difficult for organizations. Therefore, simulation has been used to troubleshoot the existing system for this study.

In addition, one of the primary and most important uses of simulations is for optimization processes (Batz, 2007). Simulation becomes useful tool when optimizing a set of parameters, especially in situation in which experiments on the real world system are difficult or not possible.

1.1. Motivation and Scope

Nowadays, production industry needs to be provided with the equipments that have recent technology due to the rapid changes and the competitive environment of global markets. New generation hardware and software suitable for particular studies are expanded every day. Unfortunately, heightening of the number of parts produced, reduction of the auxiliary energy consumption of the part can be a difficult task to cope with. At that point, an integration of simulation with an optimization solver will make us acquire goals.

In this Thesis, a simulation study performed in Type-A crankshaft production line in The Refrigerator Compressor Plant, Eskişehir to investigate into the implementation of multi objective optimization in sustainable manufacturing is presented. It has been learnt at the beginning of the study that the problem in the Plant is the huge amount of auxiliary energy consumption and the corresponding carbon emissions. In addition, Type-A crankshaft production line has been determined to have the huge amount of energy consumption in the machining department. As a result, the production line has been investigated and the necessary data has been collected.

The existing system which is integrated with the proposed model is realized. The simulation part is realized by Arena 14.0 software, and the optimization solver, OptQuest, embedded into Arena, provides simulation to be integrated with optimization.

In addition, the existing system performance under different alternative scenarios and design alternatives is discussed in detail. It can show the flexibility of the system model against changes in the production line.

1.2. Outline

In Chapter 2, a historical background about sustainable manufacturing, simulation, multi objective optimization and simulation-based multi objective optimization is discussed in detail. Application areas related with simulation, multi objective optimization and simulation optimization are categorized as manufacturing and others. The modeling and simulation tool, called as Arena, is selected for this Thesis study and introduced, and finally an optimization solver integrated with simulation model is presented.

In Chapter 3, Type-A crankshaft simulation model in The Refrigerator Compressor Plant will be discussed as a case study in detail. The model will be run and result will be reported. Then, the scenarios that were determined with the authorized people in the Plant are modeled and run again. The near optimal solution among the alternatives will be chosen.

In addition, simulation-based multi-objective optimization will be made by using the optimization solver called OptQuest which is inside the Arena simulation software. In this section, the proposed simulation model will be used as an input for the optimization solver.

The Thesis is completed with the discussion consisting of concluding remarks and recommendations for future studies.

CHAPTER 2

LITERATURE SURVEY

In Chapter 2 of the Thesis, the researches about sustainable manufacturing, multi-objective optimization, simulation, and simulation-based multi-objective optimization will be presented.

The tool whose name is ARENAwhich is of Systems Modeling Corporation in the study will be examined providing the functions of it in detail.

2.1. Sustainable Manufacturing

Nowadays, the main cause for the remaining corruption in the surroundings is the production and consumption that have unsustainable pattern. Generally, it occurs in the industrialized countries ("United Nations Conference on Environment and Development", 1992).

Continued deterioration problem of the global surrounding can be solved by making the consumption and production patternsare sustainable. Sustainable manufacturing is related with the organizations making production and offering services.

Sustainability is a quality that allows keeping, and maintaining something. Sustainability of an organization is often analyzed by three- dimensional perspectives which are environment, society, and economy (Antonio A. et al., 2007)

As humanbeings move into the future, they must simultaneously consider three interacting systems which are environment, society, and economy/ industry. They must keep, maintain, or sustain them.

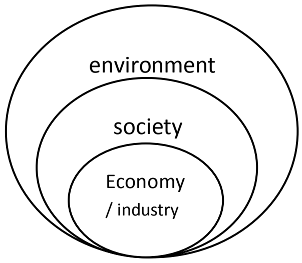

Figure 2.1 Three-dimensional perspectives analyzing sustainability

It is easily seen from the figure that society and economy are dependent on the environment. If the environment is collapsed, economy cannot survive (Former U.S. Senator Gaylord Nelson, 1996).

Sustainable Development means meeting the requirements of present generations without accepting less than users want the ability of the future to meet their own requirements.

Considering both of the importance in production in the societies and its negative effects on material/ energy consumption and carbon emissions to the environment, Sustainable Manufacturing is considered as one of the most important tasks to be addressed in following Sustainable Development (Manufacturing Technology Platform Theme: Sustainable Manufacturing, 2008).

Because manufacturing is the foundation of well-organized way of life like;

- Living,
- Transportation,
- Entertainment,
- Production,
- Safety,
- Health, e.t.c.

As such, implemention of sustainability in production environment will be one of the most positive contributions to sustainability.

Sustainable Manufacturing is a part of the Sustainable Development responding to increased awareness over the environmental effect of economic growth and global expansion of business (Leahu- Aluas, 2010).

Sustainable Manufacturing (Leahu- Aluas, 2010) is defined as the production of final parts and offering services using systems which are

- Conservation of resources,
- Safe and healthful for employees, societies, and consumers, e.t.c.

The definition mentioned above for Sustainable Production is related with;

- Usage of energy and material,
- Surrounding,
- Workers, employees and products.

2.1.1. Six Keys to Sustainable Manufacturing

Nowadays, engineers that especially design and manufacturing ones design final goods which reduce waste, protect energy and reduce pollution while manufacturing those final goods in sustainable ways. However, the environmental concerns make engineers optimize manufacturing processes and them more sustainable.

There are six ways (Hibbard S., 2009) of becoming more sustainable in production. It has been shown as the following:

- Elimination of waste,
- Recovery of energy,
- Saving time,
- Recycling,
- Reduction of pollution,
- Optimization of fossil fuel usage.

2.1.2. Eco-Efficiency

Eco- efficiency is an important component of Sustainable Manufacturing. "World Business Council for Sustainable Development" states that

> "Eco- efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the Earth's estimated carrying capacity."

Eco- efficiency is an administration strategy considered as producing more value without more negative impact. Therefore, it contributes to sustainable societies. In short, eco- efficiency is considered as doing more with less.

It provides more efficient manufacturing processes and better production and offering services while lowering usage of resources and wastes. It does not only make manufacturing save costs but also create new income sources for organisations. In addition, it makes companies in front of the market and reduces costs.

Eco- efficiency deals with process optimization, waste recycling, and eco-innovation. Implementing eco- efficiency is important in sustainable manufacturing. Eco- efficiency can be accomplished by the following approaches:

- "Reduce material intensity,
- Energy intensity minimized, dispersion of toxic substances is reduced,
- Undertake recycling, capitalized on use of renewable,
- Extend product durability, and service intensity increases" (Gök G., 2012).

There are four opportunity areas for eco- efficiency. These are redesigning of final goods, rethinking markets, re-engineering processes, and revalorizing by-products. Life Cycle Assessment helps determine the ways of optimizing eco-efficiency with product system.

2.1.3. Difference of Sustainable Manufacturing from the Others

Sustainable manufacturing is more comprehensive than green production by coping with all components of sustainability which are environment, society, and economy. It includes environmental issues like material, and carbon emissions. In addition, it is not restricted to those issues neither is it a component of an environmental management system (Leahu- Aluas, 2010).

Sustainable production uses not only technological but also non- technological solutions from selection of materials and manufacturing processes for organizational structure and mission.

2.1.4. Reasons to Adopt Sustainable Manufacturing

There are basic reasons to adopt sustainable manufacturing into the company's initiatives. These are shown as follows:

- There is a reality of climate change, critical resources for operations are scarce,
- There are pressures from all categories of stakeholders such as customers, investors, suppliers, employees, competitors, communities, e.t.c.

The well-known eco-industrial park located in Denmark (OECD, 2009) is a good example of the application of sustainable manufacturing. It has been developed through cooperation by a number of neighboring industrial companies.

2.1.5. Waste Minimization

United Nations Environmental Programme (UNEP) ("Waste Minimization", 2013) defines the Waste Minimization as:

> "Waste Minimization refers to strategies that are aiming to prevent waste through upstream interventions. On the production side, these strategies are focusing on optimizing resource and energy use and lowering toxicity levels during manufacture.

> Strategies that are considered to minimize waste and thus improve resource efficiency in or even before the manufacturing process are, for example, product design, cleaner production, reuse of scrap material, improved quality control, waste exchanges, e.t.c. on the consumption side, waste minimization strategies aim to strengthen awareness and prompt environmentally conscious consumption patterns and consumer responsibility to reduce the overall levels of waste generation."

Waste minimization often provides economic benefits like using inputs more efficiently to reduce purchases of raw materials. Moreover, reduction in hazardous waste volumes can have the effect of reducing the overall toxicity of the manufacturing process and final product, which can result in fewer employees and consumer exposure to toxins and an overall improvement in workplace health.

The environment also benefit when companies implement waste minimization strategies. These benefits are the reductions in carbon, air and water emissions as well as the conservation of natural resources that are usually associated with raw materials extraction and waste disposal. This additionally conserves water and energy used for the processing of wastes and raw materials.

Consumers with a favorable opinion of the manufacturer are more likely to purchase products from that manufacturer, and not necessarily based on the individual product's attributes.

Reduction of waste both in the final product and the manufacturing process may reduce controllable load associated with disposal and helps manufacturers stay ahead of the curve.

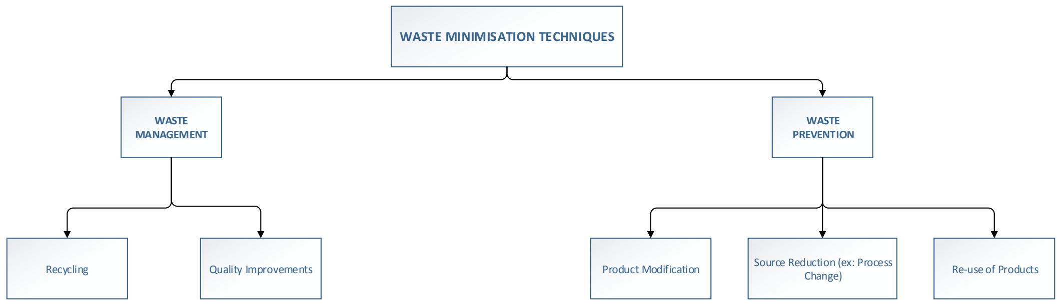

Figure 2.2 Waste Minimization Techniques in Sustainable Manufacturing ("Waste Minimization Plan", 2011)

Waste minimization techniques ("Waste Minimization Plan", 2011) consist of Waste Management and Waste Prevention. In Waste Management, recycled materials are used for another purpose, treated and reused for the same purpose, or reclaimed for another use rather than being discarded as waste. In addition, quality improvements are made to manage the waste. In Waste Prevention, product can be modified, processes can be changes or the products can be reused to prevent waste.

2.2. Indicatorsof Sustainable Manufacturing

2.2.1. Framework for Indicators of Sustainable Production

Defining Indicators:

Framework for indicators of sustainable production (ISP) begins with defining indicators and objectives. Indicators compress large amounts of information from different sources into understandable and comparable form. In short, indicators are taken into account as variables.

A variable is an operational display of system characteristic (Veleva et al., 2001). Each variable takes their values according to estimation or detection. Indicators give fundamental information about a physical, social, or economic system. They allow cause& effect relationships and trend analysis (Veleva et al., 2001).

ISPs are similar to sustainability indicators, because they point out all dimensions of sustainable development. These are environmental, social, and economic indicators. The dissimilarity of ISP from sustainability indicators is that ISP is developed for production plants, and it aims to address all aspects of manufacturing like energy and material usage, surroundings, e.t.c. (D. Krajnc, P. Glavic, 2003).

ISPs have main objectives as follows:

- Educate business about sustainable production,
- Allow for comparisons between organizations' performance in the environmental, social, occupational and economic aspects of their production,
- Provide a tool for "cross- checking" organization's mission and reporting results to interested stakeholders.

Dimensions and Qualities of ISP:

Indicator dimensions help distinguishing indicators from parameters. To set up an indicator, it is important to use four key indicator dimensions. They have been identified as follows (Veleva et al., 2001):

- Measurement unit,
- Measurement type,
- Period of measurement, and
- Boundaries.

The desirable qualities include:

- Based on accurate and available data,
- Simple, meaningful indicators,
- Addressing important global issues, …

Shortcomings of Existing Indicator Frameworks:

The most important weakness of existing indicator frameworks is lacking of clear guidance on how the indicators are implemented in practice.

Lowell Center of Sustainable Production (LCSP) Indicator Framework:

LCSP has developed an indicator framework (Veleva et al., 2001). It consists of five levels. Level one indicators measure the extent to which a company is in agreement with adjustments and in adaption to standards. Level two indicators include measures of facility inputs, outputs like emissions and waste. Level three indicators measure potential effects of a company/ facility on environmental, worker and public health. Level four indicators measure company/ facility negative effects of production within the supply chain as well as product disposition, use, and disposal. Level five indicators show how a production process of an individual company fits into the larger picture of a sustainable society.

2.2.2. Indicators of Sustainable Production (ISP) Implementation Methodology

Implementation methodology is based on using two types of indicators of sustainable production which are core and supplemental.

Core and Supplemental Indicators:

Core indicators are standard sets which are easy to be used applied at any facility. Supplemental indicators are an open set and they vary among companies.

Indicator Implementation Process:

An eight-step model is developed for definition and measurement of sustainability performance of companies (Veleva et al., 2001). The first step includes definition of sustainable manufacturing aims and objectives. In the second step, potential indicators are identified to show a company’s aims toward sustainable manufacturing. In the third step, indicators are selected for implementation.

In the fourth step, targets are set. Step five is about implementation of indicators. This is the most time-consuming step. Step six involves monitoring and results communication. Step seven involves action on results. The last step includes indicator review, policies, and goals. The process of eliminating indicators is as necessary as the process of selecting new ISPs.

The needed information and how it is used is important issues and help the company select the correct indicator (Veleva et al., 2001) in sustainable manufacturing. Therefore, there are lots of indicators used for sustainable production. Generally, indicators can be considered as energy-flow or material-flow indicators.

A collection of energy indicators is combined from several resources. Energy-flow indicators are shown according to the life cycle stages of the product and company, sector, country and product/ process levels in the Table 2.1.

Table 2.1 Energy-flow indicators ("United Nations Conference on Environment and Development", 1992),("2005 Environmental Sustainability Indicators", 2005), ("Indicators of sustainable development: Guidelines and Methodologies", 2007), ("Sustainable Manufacturing and Eco-Innovation: Framework, Practices and Measurement", 2009)

	EXTRACTION AND PROCESSING	PRODUCTION	USE	REUSE/RECYCLE	DISPOSAL
COUNTRY LEVEL	energy use	energy use	energy use	energy use	energy use
	exergy	exergy	exergy	exergy	exergy
	source of energy fraction	source of energy fraction	source of energy fraction	source of energy fraction	source of energy fraction
	average costs of energy source	average costs of energy source	average costs of energy source	average costs of energy source	average costs of energy source
COMMON	energy use; exergy; source of energy fraction; average costs of energy source				
SECTOR LEVEL	percent energy from renewable	percent energy from renewable	percent energy from renewable	percent energy from renewable	percent energy from renewable
	energy intensity	energy intensity	energy intensity	energy intensity	energy intensity
	total energy costs	total energy costs	total energy costs	total energy costs	total energy costs
	energy costs fraction	energy costs fraction	energy costs fraction	energy costs fraction	energy costs fraction
	annual energy consumption	annual energy consumption	annual energy consumption	annual energy consumption	annual energy consumption
	intensity of energy use, total, and by economic activity	intensity of energy use, total, and by economic activity	intensity of energy use, total, and by economic activity	intensity of energy use, total, and by economic activity	intensity of energy use, total, and by economic activity
COMMON	percent energy from renewable; energy intensity; total energy costs; energy costs fraction; annual energy consumption; intensity of energy use, total and by economic activity				
COMPANY LEVEL	energy use including transportation and embedded energy in used materials	energy use including transportation and embedded energy in used materials	annual energy consumption	annual energy consumption	annual energy consumption
	annual energy consumption	annual energy consumption	intensity of energy use, total and by economic activity	intensity of energy use, total and by economic activity	intensity of energy use, total and by economic activity
	intensity of energy use, total and by economic activity	intensity of energy use, total and by economic activity	specific energy consumption	specific energy consumption	total energy consumption
	specific energy consumption	specific energy consumption	percent energy from renewable	percent energy from renewable	specific energy consumption
	percent energy from renewable	percent energy from renewable	total energy costs	total energy costs	percent energy from renewable
	total energy costs	total energy costs			total energy costs
COMMON	annual energy consumption; intensity of energy use, total and by economic activity; specific energy consumption; percent energy from renewable; total energy costs				
PRODUCT/ PROCESS LEVEL	quantity of each type of energy used	quantity of each type of energy used	quantity of each type of energy used	quantity of each type of energy used	quantity of each type of energy used
	total energy use over the life cycle of a product	total energy use over the life cycle of a product	total energy use over the life cycle of a product	total energy use over the life cycle of a product	total energy use over the life cycle of a product
	share of renewable energy sources in total energy use	share of renewable energy sources in total energy use	share of renewable energy sources in total energy use	share of renewable energy sources in total energy use	share of renewable energy sources in total energy use
	total energy consumption	total energy consumption	total energy consumption	total energy consumption	total energy consumption
	specific energy consumption	specific energy consumption	specific energy consumption	specific energy consumption	specific energy consumption
	renewable energy fraction	renewable energy fraction	renewable energy fraction	renewable energy fraction	renewable energy fraction
				energy for recycling	
COMMON	quantity of each type of energy used; total energy use over the life cycle of a product; share of renewable energy sources in total energy use; total energy consumption; specific energy consumption; renewable energy fraction				

A collection of material indicators is combined from several resources. Material-flow indicators are shown according to the life cycle stages of the product and company, sector, country and product/ process levels in Table 2.2.

Table 2.2 Material-flow indicators ("United Nations Conference on Environment and Development", 1992), ("2005 Environmental Sustainability Indicators", 2005), ("Indicators of sustainable development: Guidelines and Methodologies", 2007), ("Sustainable Manufacturing and Eco-Innovation: Framework, Practices and Measurement", 2009)

	EXTRACTION AND PROCESSING	**PRODUCTION**	**USE**	**REUSE/RECYCLE**	**DISPOSAL**
COUNTRY LEVEL	land use	land use	land use	land use	land use
	material use	material use			
	material intensity of the economy	material intensity of the economy			
	domestic material consumption	domestic material consumption			
	specific material consumption	specific material consumption			
COMMON	land use				
SECTOR LEVEL	GHG emissions	percent of products designed for disassembly, reuse or recycling	GHG emissions	GHG emissions	GHG emissions
	carbondioxide emissions	percent of biodegrable packaging	carbondioxide emissions	carbondioxide emissions	carbondioxide emissions
	consumption of ozone depleting substances	GHG emissions	consumption of ozone depleting substances	consumption of ozone depleting substances	consumption of ozone depleting substances
	domestic material consumption	carbondioxide emissions	ecological footprint	ecological footprint	ecological footprint
	ecological footprint	consumption of ozone depleting substances	land use	fraction of renewable raw materials	land use
	raw materials efficiency	domestic material consumption		hazardous solid waste mass fraction	
	variety of hazardous materials	ecological footprint		hazardous solid waste mass	
	hazardous materials input mass	raw materials efficiency		solid waste cost fraction	
	material intensity	variety of hazardous materials		total liquid waste costs	
	material use	material intensity		liquid waste cost fraction	
	land use	material use		pollution mass concentration in liquid waste	
		land use		specific pollution mass ratio	
				land use	
				percent of product from recycled material	
COMMON	GHG emissions; Carbondioxide emissions; consumption of ozone depleting substances; ecological footprint; land use				
COMPANY LEVEL	GHG emissions	percent of products designed to be recycled	percent of products with take- back policies in place	percent of product from recycled material (by weight)	GHG emissions
	carbondioxide emissions	GHG emissions	total mass/ $ value of product sold	GHG emissions	carbondioxide emissions
	material use	carbondioxide emissions	GHG emissions	carbondioxide emissions	consumption of ozone depleting substances
	consumption of ozone depleting substances	consumption of ozone depleting substances	carbondioxide emissions	consumption of ozone depleting substances	generation of hazardous waste
	generation of hazardous waste	generation of hazardous waste	consumption of ozone depleting substances	generation of hazardous waste	revenues from eco products
		specific packaging costs	generation of hazardous waste	mass fraction of products from recyclable materials	revenue fraction of eco products
		material use		total solid waste mass	
		percent of products designed for disassembly,reuse or recycling		total solid waste costs	
		percent of biodegrable packaging		total volume of liquid waste	
				specific liquid waste volume	
				non- polluted liquid waste volume	
				polluted liquid waste volume	
				specific pollution mass ratio	
				pollution mass concentration in liquid waste	
COMMON	GHG emissions; Carbondioxide emissions; consumption of ozone depleting substances; generation of hazardous waste				

	EXTRACTION AND PROCESSING	PRODUCTION	USE	REUSE/RECYCLE	DISPOSAL
PRODUCT/ PROCESS LEVEL	GHG emissions	GHG emissions	kg of waste generated before recycling	GHG emissions	GHG emissions
	carbondioxide emissions	carbondioxide emissions	GHG emissions	carbondioxide emissions	carbondioxide emissions
	consumption of ozone depleting substances	consumption of ozone depleting substances	carbondioxide emissions	consumption of ozone depleting substances	consumption of ozone depleting substances
	carbon footprint	carbon footprint	consumption of ozone depleting substances	carbon footprint	carbon footprint
	total material costs	total material consumption	carbon footprint	recycled material fraction	solid waste mass for recovery and disposal
	material use	total material costs	mass fraction of products with an environmental label	solid waste mass for recovery and disposal	disposal mass fraction
		total packaging mass	product durability	recycling mass fraction	
		packaging mass fraction of the product		non- polluted liquid waste volume	
		mass fraction of reusable packaging		polluted liquid waste volume	
		packaging costs		specific pollution mass ratio	
		material use			
COMMON	GHG emissions; Carbondioxide emissions; consumption of ozone depleting substances; carbon footprint				

In addition to these indicators, there are some indicators such as operational performance, direct, indirect, relative, and eco-efficiency. Operational performance indicators (OPI) are listed by the company. The information collected is separated into direct, indirect and relative indicators. The direct indicators are the widely used category of OPI.

Environmental aspects such as waste management, emissions are measured through direct indicators. These aspects are traced by Environmental Management System (EMS).

Relative indicators consist of environmental parameters' direct measurements referred to production parameters. The usage of them is relevant for waste management and natural resources usage.

Eco-efficiency is an important component for sustainable manufacturing. It is important for companies to measure the eco-efficiency. Organizations may select measuring their eco-efficiency performance for many reasons such as monitoring and documenting performance and progress, identifying opportunities for improvement, and identifying cost savings.

If companies want to calculate eco-efficiency, the formula used is $\frac{product\ \ or\ service\ \ value}{environmental\ \ influence}$. If government wants to calculate it, the formula is $\frac{more\ \ welfare}{less\ resource\ \ use}$. This formula is called resource productivity. The indicators are separated into two groups based on the formula. These groups are product or service value, and environmental influence.

Indicators of product or service value group are quantity of products or services manufactured or offered to customers. The indicators of environmental influence are energy consumption, carbon emissions, e.t.c. The additional indicators are waste and additional financial value indicators.

Eco-efficiency reporting consists of five elements. These are organization profile, value profile, environmental profile, eco-efficiency ratios, and methodological information.

2.3. Multi- Objective Optimization

Optimization is a process of trying to find the optimum result. On the other hand, “Multi-objective Optimization (MOO)” is a process of optimizing more than one objective functions such as time, energy, cost carbon emissions, revenue, e.t.c. (Marler et al., 2004). Generally, multi-objective optimization problems include objective functions to be improved subjected to several constraints. “Multi-objective optimization” grew out of economic equilibrium and welfare and game theories, and pure mathematics.

In this study, to optimize multi objectives, Arena simulation program will be used to give the results taken from the existing system as an input into the optimization solver which is called OptQuest in Arena software.

2.3.1. Multi-Objective Optimization Methods

The methods are categorized as “methods with priori articulation of preferences, methods with posteriori articulation of preferences, and methods with no articulation of preferences and Genetic Algorithms” (Marler et al., 2004). It is found from the survey that no single solution is better.

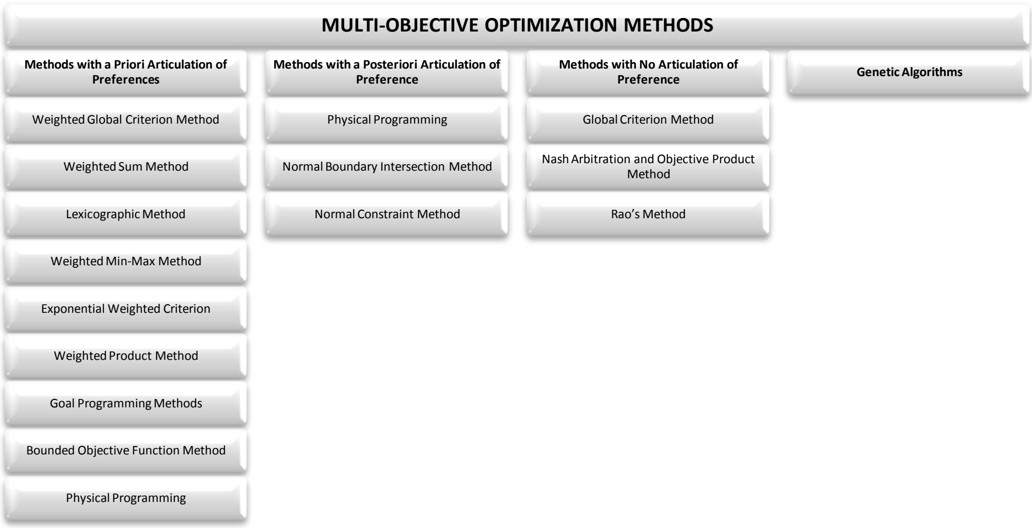

Figure 2.3 Multi-Objective Optimization Methods (Marler et al., 2004)

Methods with a Priori Articulation of Preferences:

The users are allowed to specify preferences which may be articulated in terms of goals or the relative importance of different objectives. Most of these methods include parameters such as coefficients, constraint limits, exponents, e.t.c.

The methods (Marler et al., 2004) included in this category are ranked as follows:

- “Weighted Global Criterion Method,
- Weighted Sum Method,
- Lexicographic Method,
- Weighted Min-Max Method,
- Exponential Weighted Criterion,
- Weighted Product Method,
- Goal Programming Methods,
- Bounded Objective Function Method, and
- Physical Programming”.

“The *Global Criterion* Method” is one of the common scalarization methods for “multi-objective optimization”. In this method, all objective functions are come together in order to make a single function.

“The *Weighted Global Criterion* Method” is a type of utility function where method parameters are used to model preferences. “The *Weighted Sum* Method” is the most common application to “multi-objective optimization”. According to this method, if all the weights are positive in the utility function, it means Pareto optimal. That is, minimizing the utility function is sufficient for Pareto optimality. In “*Lexicographic* Method”, the objective functions are arranged in order of importance. In “*Weighted Min-Max* Method”, a common approach for treating the utility function to be calculated for this method is to introduce an additional unknown parameter. However, when the number of constraints increases, the problem will become more complex. “The *Exponential Weighted Criterion* Method” has been proposed responding to the inability of “the weighted sum method” to capture points on non-convex portions of the Pareto optimal surfaces. “*Weighted Product* Method” is proposed to allow functions with different orders of magnitude to have similar significance and to avoid having to transform objective functions. In “*Goal Programming* Method, aims are defined for each objective function. Then the total deviation from the aims is minimized. “*Archimedean Goal Programming”* composes a subclass of goal programming where weights are assigned to the deviation of each objective from its perspective goal.

“The *Lexicographic Goal Programming”* is similar to “the lexicographic method” approach where the deviations for the objectives are ordered with respect to priority and minimized lexicographically. In “*Multi Goal Programming* Method”, various functions of the absolute value of the deviation are minimized as independent objective functions in a “multi-objective optimization” problem. In the “*Bounded Objective Function* Method”, the single most important objective function is minimized. All other objective functions are used to form additional constraints. “*Physical Programming”* was initially developed in the 1996s. This method maps general classifications of aims and objectives, and verbally expressed preferences to a utility function.

In addition, it provides a means of incorporating preferences without having to conjure relative weights. In this method, goals, objective functions, and constraints are treated equivalently as design metrics.

Methods with a Posteriori Articulation of Preference:

In some cases, it is difficult for decision makers to express an explicit approximation of the preference function, so it can be effective to help the decision maker choose from a palette of solutions. To do this, an algorithm which incorporates a "posteriori articulation of preferences" is used for determining a display of the Pareto optimal set. These methods (Marler et al., 2004) are:

- "Physical Programming,
- Normal Boundary Intersection Method, and
- Normal Constraint Method".

It is known that "*Physical Programming"* was first developed for a "priori articulation of preferences". In these types of methods, this approach is also used. It can be effective to provide "Pareto optimal" points that accurately represent the overall Pareto optimal set, even when the Pareto optimal surface is non-convex. "*Normal Boundary Intersection* Method" provides a means for obtaining an even distribution of "Pareto optimal" points for a consistent variation in the user-supplied parameter vector, even with a non-convex "Pareto optimal" set. "The Normal Constraint Method" can be used for an alternative to the last method have been discussed ("*Normal Boundary Intersection"*) with some improvements.

Methods with No Articulation of Preference:

These types of methods are chosen to be used when the decision makers cannot define what they prefer. These methods in this category are "Global Criterion, Nash Arbitration and Objective Product, and Rao's Methods".

The main idea in the most "*Global Criterion* Methods" is the usage of an exponential sum which is formed by setting all of the weights to one.

This will yield a single function. "*Nash Arbitration"* is an approach that is derived from game theory. "*Rao's* Method" is based on the use of a product-type global criterion.

Genetic Algorithms:

The methods recently discussed have included unique formulations solved using standard optimization equipments. On the other hand, approaches like genetic algorithms can be adapted for solving "multi-objective optimization" problems directly. They converge to the global solution rather than to a local solution. However, this distinction will become unclear when working with "multi-objective optimization" that usually entails a set of solution points.

2.3.2. Application Areas

Manufacturing:

Manufacturing is one of the important application fields where multi-objective optimization has been made. Some of the researchers that have done research on multi-objective optimization are shown as follows. Zhou et al. (2013) have focused on an approach that improves the analysis and make decision-making process easy. They have developed a "*discrete-event simulation model"* to take control of production flow and decision logic under real world conditions. In addition, the researchers have developed a "multi-objective genetic algorithm (MOGA)" with improving heuristics, for searching the *best solutions*.

Adinarayana et al. (2014) have presented the "*multi response optimization"* of turning parameters for turning process. In their paper, experiments have been conducted based on "Taguchi parameter design". The researchers have investigated into the use of "Taguchi parameter design" and Regression Analysis to *optimize* the material removal rate, surface roughness, and *power consumption* in turning operations using its cutting tool.

In addition, the “Analysis of Variance” has employed to analyze the effect of process parameters during turning process. Singarvela et al. (2014) have estimated the *optimum machining parameters* using Taguchi based utility concept with “Principal Component Analysis” on turning in their experimental analysis.

Others:

Multi-objective optimization is made in not only manufacturing but also the other application areas. Marler et al. (2004) have done research on the current continuous *nonlinear “multi-objective optimization”* concepts and methods for engineering. They have classified methods into three parts which are “methods with priori articulation of preferences, methods with posteriori articulation of preferences, and methods with no articulation of preferences”. All of the references are categorized in Appendix D.

2.4. Simulation

“Simulation” is explained as the process of designing a real or proposed system model and making experiments with it for the purpose of either understanding the actions of the real system for a given set of conditions or evaluating various scenarios for the operation of the system. The term simulation generally shows the basic framework of simulation principles.

In the first part of the simulation definition, real or unreal system means there exists a layout or a process to be modeled or it means that the model can be a modification of the real system or it can be imaginary. The imaginary systems show that they are alternatives to the real systems and wholly original ones.Simulation has been ranked higher than other more traditional operations research tools such as queuing theory and linear programming in the 1970’s (Kelton W., 2008).

Simulation models can be classified as static vs. dynamic, continuous vs. discrete, and deterministic vs. stochastic. These classifications are defined as follows:

- Static vs. Dynamic: Time does not play role in static models, but in dynamic models. Therefore, in this Thesis, the simulation model is a dynamic model.
- Continuous vs. Discrete: In a continuous model, the state of the system can continuously change over time while it can change at separated points in time in a discrete model.
- Deterministic vs. Stochastic: Deterministic models have no random input while stochastic models have at least one random input.

2.4.1. Lifespan in Simulation

The Early Years in Simulation:

In general, Simulation was professional equipment which was used by large companies in the 1950s and 1960s. In the early years, typical simulation users were found in aerospace and steel corporations.

The Formative Years:

The usage of simulation, known nowadays, began during the 1970s. Computers were becoming cheaper and faster, and the value of simulation was realized by other industries.

The Recent Past:

Simulation began to establish its roots in business because of the introduction of the personnel computer and animation during the late 1980s. In spite of the fact that simulation was still being used to analyze failed systems, many people were requesting simulations before production was to begin. After 1980s, the value of simulation was recognized by larger firms, but simulation was rarely used by smaller firms.

The Present:

Simulation began to spread during the 1990s. Many smaller firms took the equipment and saw use at the early stages of projects in which it could have the greatest impact. Faster computers, easy integration with other packages, and the emergence of simulators have helped simulation become standard equipment in many companies.

The manner where simulation is used has changed; it is being employed earlier in the design phase and updated as changes are made to operate systems.The major difficulty preventing simulation from becoming a well- utilized tool are modeling skills and model- development time required for development of a successful simulation.

The Future:

J. Carson and D. Brunner (2000) state that simulation software will be more widely used for real- time decision making rather than the traditional off- line methods.

Nowadays, simulation is becoming possible to guess the complete integration of simulation with other software packages which collect, store, and analyze system data at the front end along with software which helps control the system at the back end.Simulation tools are being developed to back up distributed model- building, processing, and remote analysis of results.

Nowadays, simulation projects focus on complicated systems' design. They often must deal with complex- system- control issues which can lead to the development of new system- control logic which is examined by the cultivated simulation.

2.4.2. Steps in Simulation Process

Kelton et al. (2008) identifies several stages that are included in a computer simulation. For the beginning of the assembly line simulation study, the existing system should be understood and the goal of the simulation study should be identified.

In the next step, the formulation of the model representation is created. The creation is made with respect to flowcharts or mathematical models. Subsequently, the formulation is transferred into modeling software using programming languages or particular software that is adapted into the requirements of a simulation process. Modeling approach is generally difficult because of the high quantity of information and data required for setting the human models and the plant layout elements (Hosseinpour F. et al., 2009).

After program creation, the program should be verified.It means that computer presentation represents the conceptual model faithfully (Kelton et al. 2008). In short, the question of did the qualified person build the model right can be asked to show the term verification (Park S. et al., 2006).

The next step of the simulation study is the validation of the model with something similar to the existing system. In short, validation answers the question of did the qualified person build the right model (Park S. et al., 2006). It is important for a model to be reliable; in other respect, the results may not be used in the decision- making process if the simulation model is already valid. It is easily understandable that validation of the model is not sufficient itself for decision making.

In the next step, experimentation that includes both designing experiments to identify the performance measures to be used with enough confidence and making these designed experiments by effectively using computers, is made on the developed model.

Finally, the results of the running process are analyzed. It means that conclusions are drawn from output that assists in decision- making process. If there is no problem so far, documentation is made.

2.4.3. Model Types of Simulation

As Kelton et al (2008) has mentioned that on the one hand, physical models that are the most realistic types among the others, include the tabletop models acting like a prototype or miniature readings of the existing system or facility, full- scale readings of the actual facilities used for experimentation, e.t.c.

On the other hand, the unreal models can also be transferred into analogous computer programs. These programs make use of approximations and assumptions for representing the actions of the real systems.

2.4.4. Advantages of Simulation

Simulation has many benefits for users. J. Banks (2000) outlined that it makes users do choose the correct alternative among the possible ones, allows users to examine possibilities of new methods, provides time flexibility which means expansion or compression in keeping with the type of the simulated activity.

Simulation also helps easily diagnosing problems of the complicated systems which are generally impossible to be solved within the existing system, identifying constraints acting like a bottleneck of the systems, and visualizing the system with animations of computer software.

With the help of simulation, preparation for changes is easy in the existing system by considering the possible what- if scenarios. Simulation (Park S. et al., 2006) can control sources of variation and level of detail. It facilitates replication and can restore the system state.

2.4.5. Disadvantages of Simulation

Although there are important advantages of simulation, there are also disadvantages that cannot be ignored. Banks (2000) has mentioned four main disadvantages that should be considered.

The first one is the requirement of special training for building a model and it is highly unlikely that models will be the same when it is generated for the same system and by different modelers. The second disadvantage is the difficult interpretation of the simulation results. Most simulation outputs may be hard to find out whether detection is a result of the real environment randomness or interrelationships as they are essentially random variables based on random inputs. The other disadvantage is the time consuming and being expensive of modeling simulation especially when enough resource is not allocated for modeling and analysis processes, resulting in a simulation model and/ or analysis that are not sufficient to the task. The last disadvantage mentioned by Banks is that simulation may be used inappropriately especially when an analytical solution is possible.

2.4.6. Application Areas

Simulation has spread among all the application areas. The application area of simulation is not restricted to production plants, hospital facilities, transportation, personal- service operations, computer network, logistics and distribution operation, chemical plants, criminal justice system, freeway system, business process, fast- food restaurants, supermarkets, emergency response systems, theme parks.

Application areas have been divided into two fields which are manufacturing and the other areas in the following two sections. Although the subject of the Thesis is under the production field, other applications in different areas provide insight for different aspects of simulation.

Manufacturing:

Manufacturing systems are one of the important application fields for “simulation modeling”. Its first uses have dated back to the early 1960’s (Hosseinpour F. et al., 2009). Since then, it has been used in the design and analysis steps of manufacturing systems. Law (1999) has identified issues used by simulation for addressing in production. These are shown as follows:

- Requirements such as number, type, and physical arrangements for transporters, conveyors,
- Information about machines for a specific objective,
- Information about inventory buffers,
- Evaluation of a change in product mix or volume,
- Evaluation of the effect of a new piece of tool on an existing manufacturing system,
- Number of shifts,
- “Throughput analysis”,
- “Time- in- system analysis”,
- “Bottleneck analysis”,
- Production scheduling,
- Control strategies,
- Reliability analysis like the effect of preventive maintenance,
- Inventory policies,
- Quality- control policies,
- Utilization of equipment or personnel,
- Timeliness of deliveries,
- Queue sizes, and
- Times parts spend in queues

Several investigators have used simulation techniques in the field of manufacturing for their study so far (Hosseinpour F. et al., 2009). Some of their studies are related with energy-efficient manufacturing, one of the necessary tasks in recent years.

Rahimifard et al. (2010) have proposed an approach for *energy efficient manufacturing* through modeling breakdown of energy required to manufacture a single finished good. Aim of this search is to show how the product and the production efficiency are evaluated using an "Embodied Product Energy (EPE) Model". In this model, activities are focused on the auxiliary energy to be minimized. In addition, efficiency ratios for one process, for one product and for the production system are taken into account.

According to Rahimifard and Seow (2011), the *energy consumption* in production plants can be lowered by either through improved energy check used in substructure and technical services or using more efficient technologies and tools.

Their research adopts an approach to modeling energy flows within a production system based on a "product" viewpoint, and utilizes the energy consumption data at "process" and "plant" viewpoints for providing energy breakdown such as direct which consists of auxiliary and theoretical, and indirect used during production. Direct and indirect energy are come together to generate the Embodied Product Energy (EPE). The EPE model has been prepared to provide that energy hotspots can be easily seen in the system and the improvement activities can be made on those hotspots.

Kara et al. (2011) has presented an "*innovative energy oriented simulation model*" for manufacturing system planning. They proved that besides taking into consideration single machine/ process, the perspective on process chains and plants as a whole supports further potentials for improvement.

Simulation is used for making more than one alternative design to the existing system and find and select the best one. For example, Scriber has used simulation to select the best probable production system from proposed ones and described this study as a case study (Scriber T. J., 1991). Azadeh (2010) developed an integrated simulation model that generates optimum production alternatives in a steel- making factory. Altiparmak et al. (2002) have used simulation meta-models as intelligent techniques to optimize buffer sizes in assembly systems.

Some of the researchers have used simulation for system analysis. For example, Patel et al (2002) have used “discrete- event simulation” to analyze process layout, operator staffing, repair and service routing logic, first time success rate, and random equipment breakdown in automobile sector. Methods are offered for discrete manufacturing processes especially for the Final Process System to optimize resources.

Choi et al. (2002) have discussed about implementation of simulation modeling as an analysis tool and visual management at an automotive sector. Gurkan et al. (2005) have investigated into the application of simulation technique in weaving mills.

Simulation can be used for scheduling problems in manufacturing field. For instance, Potoradi et al. (2002) have described finished goods scheduling using simulation for meeting demand.

Simulation can be used for activities in the field of production and assembly line. Kibira et al. (2002) have presented a virtual- reality simulation of a production-line design for finished good. Wiendahl et al. (1991) have used simulation equipments in the assembly planning area and the equipments are divided into assembly shop, cell, station, and component because of different objectives of the different efforts.

Simulation is generally used in order to see the changes to be made in the existing system in advance and alter the system in the right manner, respectively. Williams (2002) has presented that simulation is useful in studying the negative effects of system failures and delays on the output and cycle time of products. Heilala et al. (2008) have reviewed some suitable approaches for "environmental impact analysis" during system development and linked lean manufacturing into environmental impacts. Their major aim is to use "Discrete Event Simulation" for environmental impact analysis.

The simulation studies of the researchers consist of the auxiliary programs for simulation. Rogers (2002) has used OptQuest optimization solver as a tool in order to apply simulation tools that seek optimum results to manufacturing system design and control problems. Altinkilic (2004) has showed the usage of simulation for improving shop floor performance. He has shown the performance evaluation of the real system by using ARENA software.

Manufacturing cells are performed, the new system acting is easily compared with acting of the real one thanks to the motivation of redesigning the shop flow.

The literature about simulation usage extends back for about two decades comprising different aspects of manufacturing, taking into account capacity and production planning, scheduling, sales and after sale services, e.t.c.

Others:

The example studies given below reflect the application areas of simulation apart from manufacturing. It is seen that application areas are unlimited and the simulation studies show brief information that makes users understand applications.

Chen (2002) has used simulation for providing a decision support mechanism for logistics activities. Simulation model helps the authors determine capital equipment requirements and alternative strategies for logistics operations. In spite of not proposing a new concept and their object-based approach, their "discrete event simulation" model simulating continuous production flow is important to be mentioned.

Policy is an application area of simulation as well. Simulation has been used to help policy makers evaluate decisions on the topics of emergency planning, traffic, and health management. Köse (2003) has discussed the traffic management and advised on the future of the city considering marine traffic that is involved in the application of simulation.

Military problems and health care are some of the other application areas. Hill (2001) and Standridge (1999) have studied them in their studies respectively. Graves et al. (2002) have studied on military requirements together with logistics in their simulation studies. In addition, they have illustrated the potential impact of simulation in supply, transportation and maintenance application areas.

Business processes in service sectors have been considered as a simulation application as well (Dennis et al., 2000). Customer service in a telecommunication firm is subjected to the study for defining the operating principles, service vision, processes, e.t.c. Proposed simulation model has helped predicting what effects of the alternative solutions on service quality, resourcing, cost, and process efficiency.

Nsakanda and Turcotte (2004) has worked on simulation to evaluate and analyze air cargo operations at one of the new cargo plants at an Airport. The airline's cargo operations and the simulation modeling approach have been described briefly. They have proved that the proposed simulation- based equipment could be effectively used ftro evaluating quantitatively and compare different policies, business practices and procedures within a set of constraints.

2.4.7. Simulation Tools

There are several methods that create simulation models on computer. General computer programming languages like “FORTRAN, Basic, or C/ C++” can be found from the literature (Law and Kelton 1991). Ssimulation language is a software package where model is developed by programming.

Simulation tools can be classified as general- purpose simulation languages, simulation front- ends and simulation packages. The general- purpose simulation languages require the user to be both proficient programmer and competent simulation user. The simulation front- ends are interface programs between simulation language being used and the user. Nowadays, the simulation package utilizes constructs and terminology common to the manufacturing community, and offer animation and graphical view. Graphical- model building approach has been preferred instead of using simulation-model building approach so far.

Examples of simulation languages are “*ARENA*, AweSim, Extend, Automod, Promodel, Witness, Flexsim, Goldsim, Mast, SimCad”, e.t.c. Web addresses of simulation tools for further information are shown in the below Table 2.3. It should be noted that all of the tools are not limited to the tools written as above. There are several simulation languages in business activities. The tools in Table 2.3 are selected among the softwares which have considerable shares in business activities.

Table 2.3 Simulation software in the market (Fu, 2002)

Name of the Simulation Tool	Web Addresses for Further Information
Automod	http://www.autosim.com
Promodel	http://www.promodel.com
ARENA	***http://www.arenasimulation.com***
AweSim	http://www.pritsker.com
Witness	http://www.lanner.com
Flexsim	http://www.flexsim.com
Extend	http://www.imaginethatinc.com
GoldSim	http://www.goldsim.com
Mast	http://www.cmsres.com
SimCad	http://www.createasoft.com

2.4.8. ARENA

The ARENA modeling system from Systems Modeling Corporation is a powerful and flexible equipment allowing analysts for creating animated simulation models that accurately represent any system. ARENA, first released in 1993, employs an object- oriented design for entirely graphical model development.

Simulation users place modules which are graphical objects on a layout for defining system components like operators, machines, and material handling equipments such as conveyors.

ARENA has many unique properties given as follows:

- ARENA has a natural and consistent modeling methodology because of its flowchart- style model building regardless of complexity. Even the flowcharts of systems which have been created by Microsoft Visio can be imported and used directly.
- It is extendable and customizable results in re-creatable, reusable templates adapted to particular applications.

- The scalable architecture of ARENA provides a modeling medium which is *easy* to suit the needs of the beginner and *powerful* enough to satisfy the demand of the advanced users.
- ARENA can be easily interacted with applications like Microsoft Access and Excel with its built- in spreadsheet data interface.
- There is essentially no boundry on creating interfaces.

With advantages mentioned above, ARENA has become the academic standard, which is taught in several Industrial Engineering schools all over the world, and also encouraged the Integrated Manufacturing Technologies Research Group to get an academic license of the program.

ARENA Tools and Features:

An integrated framework is provided by ARENA in order to build simulation models in several applications. Hammann (1995) states that an overall simulation project may be finished within the ARENA software, whereby integrated supports provided for functions needed for completing a successful simulation which includes input and output data analysis, model building, animation, model verification, e.t.c.

ARENA Input Analyzer can be used for processing and classification of the obtained data which is needed for input data analysis. Suitable probability distributions can be achieved for simulation models. The model building window in ARENA helps the users easily convert flowcharts into functional models.

Like the “input data analysis”, Output Analyzer also helps the users carry out statistical analysis on the results taken. Last But Not Least, the Process Analyzer helps examining the chosen results of several scenarios depending on selected controls on the system.

Animation that accompanies the model is a fascinating feature in a simulation study. Generally, watching animated actions on graphs are more attractive than straight numbers and texts. Animation tool of ARENA helps the users to pass their studies, and results to the users easily. ARENA animations can be created in several ways such as the following:

- Using ARENA's graphics drawing tools, From AutoCad,
- In other tools and imported to ARENA via Active X,
- Using other Windows- compliant drawing systems which can be pasted into ARENA layouts,
- Or any combination of the others mentioned above.

ARENA program consists of several animation options for real time representation of model statistics. The user can directly place histograms, dynamic plots, and time clocks within a simulation for showing system status as the model performs. Takus (1997) has mentioned that this information is shown on a real-time basis as well as on a post- process basis in the ARENA statistical summary report.

2.4.9. Researches about the Activities Not Including Multi-Objective Optimization and Simulation for Manufacturing, Minimization of Energy Consumption, and Waste

In the literature, lots of activities which do not consist of simulation or multi-objective optimization on energy efficiency and waste management exist. The related studies are discussed as the following:

Energy:

In the title of "Smart, Safe and Sustainable Manufacturing" by Rockwell Automation (2009), "greenprint" methodology has been applied for energy management from identifying where energy is used, to measuring and monitoring high energy using areas and then determining how to better control and optimize that energy consumption.

A system which is called RSEnergy Metrix System is used to identify largest energy consuming areas, biggest opportunities for cost savings, and as resources become available, targets for future investment to gain further energy reductions.With the help of RSEnergy Metrix, data are gathered from more than 60 power monitors installed throughout the Milwaukee, WI headquarters campus. By using their metrix, energy usage reduced by 4 million kilowatt hours that resulted more than $230000 in annual savings.

Liu et al. (2012) have presented a system monitoring energy efficiency without torque sensor and dynamometer. The system only needs a power sensor for estimating input power of spindle system. They have proved that changing cutting parameters made improvement on energy efficiency. Moreover, the system has made the energy consumption and machine utilization available in real time.

Zein et al. (2012) have proposed a methodology that presents different energy consumption monitoring procedures based on standardized work pieces. Energy consumption characteristics of the studied machine tools have been compared and the potential of using the obtained data for energy labeling of machine tools have been discussed in their study.

Dietmair and Verl (2009) have presented methods to forecast the actual power drain profile and to optimize machines for minimal energy consumption under alternative scenarios. One of the main advantages of their model is the easily extendibility with additional sub-models.

Guo and the others (2012) have proposed an approach incorporating energy consumption and surface roughness in order to optimize the cutting parameters in finish turning. Babu et al. (2012) have made experiment to select appropriate cutting parameters that ensure less power consumption in high tare CNC machines.

Experiment has been conducted using Taguchi's technique with process parameters. Then, power consumed, the output characteristic was measured with the help of a data acquisition system. Besides, the data were analyzed and process parameters like depth of cut and spindle speed, were selected for minimum energy consumption.

Liu et al. (2012) have designed a questionnaire for measuring industrial energy saving activities and identify their major determinant factors by an empirical study of "small and medium-sized enterprises (SMEs)" in China. The findings in their study show that Chinese policy makers should gradually expand the regulative requirements currently focusing on the large energy-consuming companies to "SMEs".

Waste:

Driussi et al. (2006) have reviewed examples of how technology can be used to minimize water, noise pollution, e.t.c. in the mining industry. They have pointed out that waste minimization can be accomplished through reduction of waste production, waste collection, and the neutralization of pollutants.

Begum et al. (2006) have made a case study consisting of construction waste generation, composition, recycling and reuse in the site. They have analyzed the economic feasibility of waste minimization by performing a benefit-cost analysis.

Manufacturing:

Brinksmeier et al. (1998) have described different methods for modeling and optimization of grinding processes. In their study, at first, process and product quality characterizing quantities are measured. Then, different model types such as physical and empirical basic grinding models and empirical process models based on neural networks, fuzzy set theory and standard multiple regression methods are discussed for an o€-line process conceptualization and optimization using a genetic algorithm.

Afterwards, a target tree method has been used to assess the grinding process results which build the individuals in the genetic algorithms' population. The methods which have been presented are integrated into an existing grinding information system that is part of a three control loop system for quality assurance.

2.5. Simulation-Based Multi-Objective Optimization

Simulation models provide insight on the behavior of various types of complex systems (Editorial, 2014). Decision makers can benefit from these simulation models generally in two ways such as the following:

- The results of simulation- based analysis are used to improve the existing system performance under study by some specific changes to its design parameter values.
- The simulation model is analyzed repeatedly to find a set of design parameters providing the best which is simulated performance.

There is an approach called simulation-optimization which combines simulation and optimization to give the best solution to the application field. "Simulation optimization" shows methods that search design points which are vectors including all input variables within the design space to optimize performance measure (Fu, 2002). In other words, Carson et al. (1997) have stated that "simulation optimization" can be considered as the process of finding the best input variable values among all possibilities without explicitly evaluating each of them.

Many studies such as ranking and selection (e.g. Smarter method), random search and meta-heuristics have been made to get the best solution especially when the simulation experiments do not require too much computing time. When the function to be optimized is differentiable, derivative-based methods or metamodel-based optimization are often exploited.

While an internet search that uses a web browser with a keyword of ‘‘Simulation Optimization’’ brings about more than thousand pages, the “Google Scholar” gives about more than twenty thousand pages ranging from technical and scientific articles, research reports, conference publications, books to software, consultancy, e.t.c.

It is clear that “simulation–optimization” is a field that captures as much interest from researchers and simulation users dealing with real problems.The results of the researches about simulation-optimization will be clear that optimization routines have been recently incorporated into several commercial simulation software packages such as Arena OptQuest.

The goal of an optimization solver is to compose the simulation of a sequence of system configurations so that a system configuration will be finally obtained that it provides optimal results.

Nowadays, a common goal in the optimization and simulation societies is building up methods to help the users produce high quality solutions in the absence of tractable mathematical structures. It is clear from the researches that several issues are become known in the area of simulation-optimization to enlarge the number of problems that can be handled using this approach and to improve the existing methodologies. Requirements (Bowden et al., 1998) for an automated simulation optimization tool were formulated for users in the 1970s.

Hall et al. (1998) have discussed six domains common to any automated simulation optimization tool. These domains are “Methods, Classification, Strategy and Tactics, Intelligence, Interfaces, and Problem Formulation”.

In the “Methods Domain”, optimization methods used to optimize represented systems are addressed. “Analysis and Classification” of a given optimization problem are addressed in the “Classification Domain”. In the “Strategy and Tactics Domain”, the profession of simulation optimization is addressed for making the most efficient use of computing resources and increasing the accuracy of the observed optimal solution. The intelligence in the solver is considered in the “Intelligence Domain” for selecting the strategic approach used for an optimization study. Both the interface between the optimization solver and the user; and the interface between the optimization solver and the simulation model are addressed in the “Interfaces Domain”. Finally, in the “Problem Formulation”, the creation of the objective function and constraints to help the optimization solver are addressed.

2.5.1. Simulation Optimization Methods

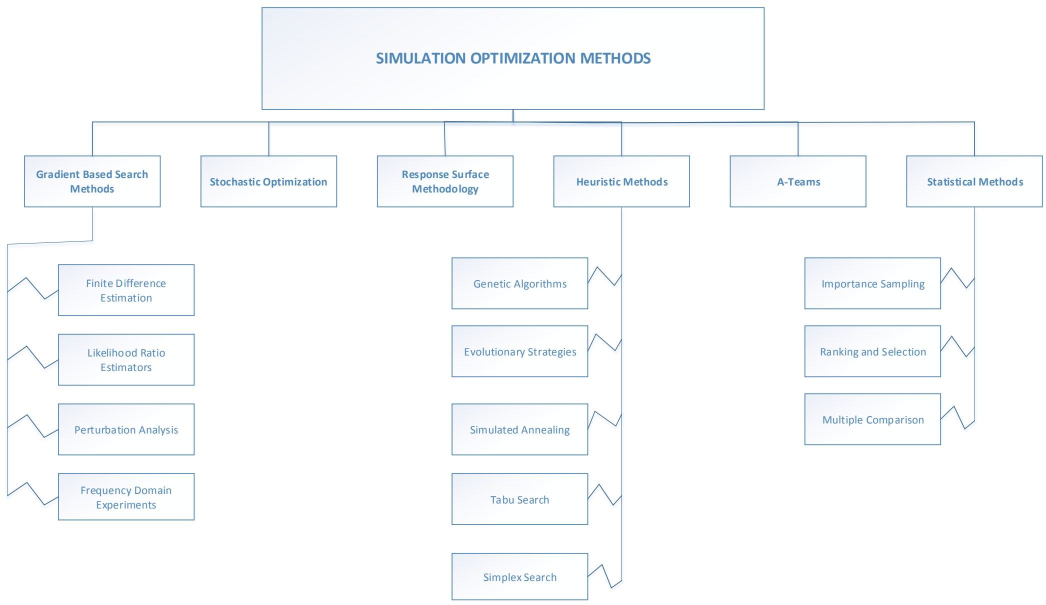

Figure 2.4 Simulation Optimization Methods (Carson and Maria, 1997)

Simulation Optimization Methods are classified in the above Figure 2.4 as "Gradient Based Search Methods, Stochastic Optimization, Response Surface Methodology, Heuristic Methods, A-Teams, and Statistical Methods" and the information of them is written as follows:

1. Gradient Based Search Methods:

Methods such as "Finite Difference Estimation, Likelihood Ratio Estimators, Perturbation Analysis, and Frequency Domain Experiments" estimate the "response function gradient" to assess the shape of the objective function and employ deterministic mathematical programming techniques.

- According to Azadivar (1992), "*Finite Differences"* is the most immature method of estimating the gradient.
- *"Likelihood Ratios Method"* is defined as the expected value of a function of Input and Simulation parameters. Glynn (1989) and Reiman and Weiss (1986) have discussed LR methods in their studies.
- *"Perturbation Analysis"* can be classified as "smoothed and infinitesimal perturbation analysis, and infinitesimal perturbation analysis' variants".

All partial gradients of an objective function are measured from a single simulation run in "infinitesimal perturbation analysis". The idea of this analysis is that if an input variable is perturbed by an infinitesimal amount, the sensitivity of the output variable to the parameter can be estimated by tracking its pattern of dissemination.

The fact that all derivatives can be derived from a single simulation run shows a significant advantage in terms of computational efficiency, however, the estimators derived using IPA are often inconsistent.

- In “*Frequency Domain Method* (FDM)”, the input parameters chosen are vibrated sinusodially at different frequencies during one simulation run. The output variable values are subjected to “Fourier Analysis” (Morrice and Schruben, 1989). “FDM” was iniatially introduced as a screening tool for continuous input factors in “discrete-event simulations” (Schruben and Cogliano, 1987).

2. *“Stochastic Optimization”* is the problem of finding a local optimum for an objective function whose values can be measured or estimated.
3. *“Response Surface Methodology* (RSM)” is a procedure in which a series of regression models are fitted to the output variable of a simulation model and the resulting regression function is optimized. In addition, “RSM” requires a smaller number of simulation experiments relative to many gradient based methods.
4. *“Heuristic Methods”* such as “Genetic Algorithms, Evolutionary Strategies, Simulated Annealing, Tabu Search, Nelder and Mead’s Simplex Search and A-Teams” are frequently used for “simulation-based optimization”.

- *“Genetic Algorithms”* employ random choice to guide a highly exploitative search, striking a balance between exploration of the feasible domain and exploitation of good solutions (Holland, 1992).
- Similar to the Genetic Algorithms, an “*Evolutionary Strategy”* is an algorithm imitating the principles of natural evolution as a method for solving parameter optimization problems.
- *“Simulated Annealing”* is a stochastic search method which avoids getting stuck in local optima and tracks the best objective value overall. In addition, it performs well on combinatorial problems.
- *“Tabu Search”* is a heuristic method which is used to solve combinatorial optimization problems ranging from graph theory to pure and mixed integer programming problems.

- *“Nelder and Mead’s Simplex Search”* is a heuristic method which starts with points in a simplex that consists of “p+1 vertices” in the feasible region. It progresses by dropping the worst point continuously in the simplex and adding a new point determined by the reflection of the worst point through the centroid of the remaining vertices.

5. An “*Asynchronous Team* (A-Team)” is a process which includes combining various problem solving strategies so that they can interact synergistically.

   It is inherently suitable for “multi-criteria simulation optimization problems”. Therefore, it represents one of the fastest extending areas of simulation optimization research.

6. *Statistical Methods:*

- *“Importance Sampling Methods* (ISM)” have been used to achieve significant speed ups in simulations including rare events, like ATM communication network or failure in a reliable computer system (Shahabuddin, 1995). The basic idea of ISM is that the system is simulated under a different probability measure so as to increase the probability of typical sample paths that involves the rare event of interest. The main problem in this method is to come up with an appropriate change of measure for the rare event simulation problem at hand.
- *“Ranking and Selection (R&S) Methods”* such as “SMART”, “SMARTER”, are frequently used for practical problems like finding the best combination of parts manufactured on various machines to maximize productivity or finding the best location for a new plant to minimize cost.

  In these types of optimization problems, some information of the relationship among the alternatives is available. The optimization problems can be treated by R&S Methods as multi-criteria decision problems.
- *“Multiple Comparisons With the Best* (MCB)” is an alternative to ranking and selection method when the problem is to choose the best of a finite number of system designs.

2.5.2. Application Areas

Manufacturing:

Most of the articles about simulation optimization cover a variety of important and challenging topics. They highlights new methodologies, improve the knowledge about how simulation-optimization is used and contribute to application-oriented problems by addressing theoretical issues arising in manufacturing, transportation, energy management, supply chain management and engineering.

Huerta-Barrientos et al. (2014) analyze the structure, collaboration patterns and the time-evolution of the co-authorship network of simulation-optimization of supply chains. According to this article, it is stated that although simulation-optimization methods are numerous, they have not yet been extensively applied to back up decision-making in the fields of supply chain and manufacturing.

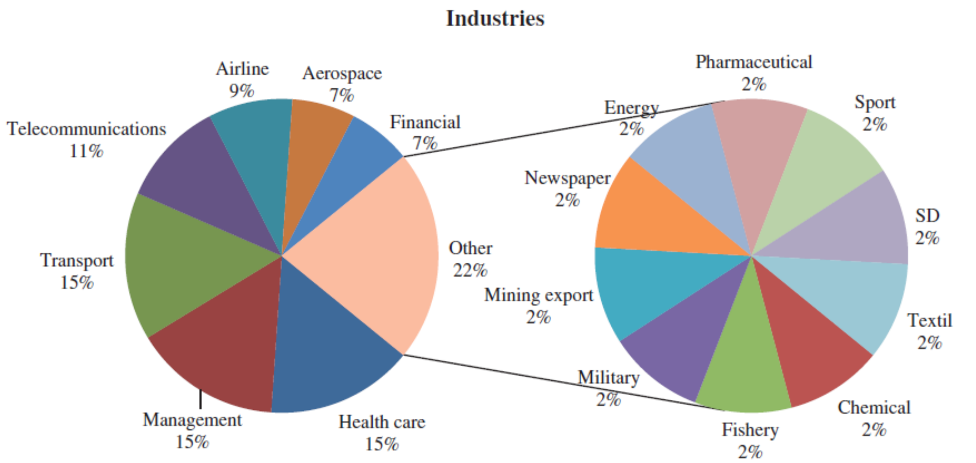

Figure 2.5 Industries supported by Simulation Optimization methods (Huerta-Barrientos et al., 2014)

Industries that have been backed up by "Simulation Optimization" methods and techniques within a determined year range are shown in the Above Figure 2.5. Industries are categorized as airline, aerospace, financial, telecommunications, transport, management, healthcare, and others which are energy, pharmaceutical, sport, SD, textile, chemical, e.t.c.

Table 2.4 Manufacturing activities supported by Simulation Optimization methods (Huerta-Barrientos et al., 2014)

Manufacturing
Production Planning
Production line
Process plant design
Flexible manufacturing
Automated manufacturing system
Lean manufacturing
Robot manufacturing cell
Buffer allocation
Scheduling
Assembly line

Manufacturing activities assisted by Simulation Optimization methods are displayed in the above Table 2.4. It is seen that "production line" is supported by those methods explained before. Therefore, a Simulation Optimization method has been applied for Multi-Objective Optimization on the Type-A crankshaft production line.

Some of the researchers have studied on optimization using discrete-event simulation model in manufacturing. For example, Apak and Ercan (2012) have developed a World Line Card Production System simulation to evaluate the *optimality of existing production line* via using *discrete event simulation model* with variety of alternative proposals. They have analyzed the current production system by a simulation model emphasizing the bottlenecks and the poorly utilized production line. Zhou et al. (2013) have developed a "*discrete-event simulation model"* to capture production flow and decision logic under real world conditions. They have developed a "multi objective genetic algorithm" improving heuristics for searching for the best solutions.

They have made experiments via a prototype system built up for verifying and validating such as sensitivity analysis of related model parameters. Matta (2008) has proposed a mathematical programming display of discrete event systems that can be used for optimization while some performance measures are contemporarily calculated.

There are lots of simulation optimization softwares in the market. OptQuest which is a part of the Arena simulation software is one of these optimization tools. Some of the researchers have studied on simulation-based optimization using this solver. For instance, Caputo et al. (2009) have presented a simulation model that allows the elaboration of an operative plan of production through the verification of finite capacity scheduling of resources. Their model has minimized costs of stocking, set-up, considering other production costs as constant. The optimization tool, *OptQuest* in Arena allows an optimal solution, approving the validity of the study of new applications of the simulative instrument for the verification of productive capacity in the short term.

Eskandari et al. (2011) have evaluated and compared two commercial "simulation-based optimization" packages which are "*OptQuest"* and "*Witness Optimize"* for determining their relative performance based on the quality of obtained solutions in a reasonable computational effort. For performance evaluation and comparison of these two packages, two well-known benchmark problems, the pull system and the inventory system, are used.

Law et al. (2002) have discussed available optimization packages and their search techniques. In their study, they have chosen two commercial optimization packages to apply to a manufacturing example with more than one decision variables. Then, they have given the results obtained from their applications in the manufacturing field. Melouk et al. (2013) have prepared a simulation model that captures the complex nature of the system while an optimization solver searches the solution space and sends trial solutions to the simulation for evaluation.

Willis et al. (2008) have developed “SimMOp” framework for generating solutions to simulation-based multi objective optimization problems. This framework will combine a simulation model, a search algorithm with an embedded “multi objective optimization method” and database technologies for generating a set of good quality solutions.

Energy-related studies made by some researchers are investigated as follows. Zhu et al. (2014) have investigated the application of a Model Predictive Controller, equipped with linear-programming based optimizer with application to *energy management* in production environments. Their studies have proposed a feedback loop structure to help *energy/production planners* make decisions using different objectives and under different constraints, thus descriptive and prescriptive scenarios can be applied. Herrmann et al. (2009) have presented an integrated concept to cherish *energy efficiency* in manufacturing firms on technical building services, production process & machine, production system, e.t.c.

There has been a simulation approach in that concept that enables to derive and evaluate organizational as well as technical measures to increase energy efficiency with respect to economic and ecological objectives. Optimization with process chain simulation has been made in order to search for an optimal solution considering “energy per part” for the production line.

Dao-fei et al. (2010) have proposed an optimization model to improve the efficiency and performance for production planning in “steelmaking and continuous casting (SCC)” process. They have described the optimization model combined with several algorithms. In addition, a simulation model to analyze and evaluate production plans has been presented. Then, the integrated system that consists of optimization and simulation models has been introduced to evaluate and adjust the production plan on-line.

Rani et al. (2010) have done research about simulation, optimization and "simulation-optimization" modeling approach and provided an overview of their applications in their literature. They have pointed out that Optimization methods have been proved of much importance when they are used with simulation modeling and the two approaches (optimization and simulation) when combined together give the best results in the application area.

Othman et al. (2012) have overviewed a simulation method in supply chain management (SCM) fields. They have made studies on simulation modeling and tools which have been discussed by previous researchers.

Shadiya et al. (2012) have presented a simultaneous approach to maximize profit, while minimizing waste through source reduction with the implementation of "multiobjective optimization" with process simulation. Their approach has involved four steps. These have been process modeling and analysis, identification and selection of process alternatives, and incorporation of multi objective optimization.

2.5.3. Simulation Optimization Software

Nowadays, it is important for many simulation software developers to find optimal solutions for applications as soon as possible. Some of the researchers have surveyed three recent and practical techniques and a brief discussion of major software packages that employ them (Batz, 2007).

OptQuest is one of the software packages used for integrating simulation, and optimization (Glover et al., 1996). Besides, it handles multiple objectives and constraints on the input variables.The well known optimization packages are listed in the following Table 2.5.

Table 2.5 Optimization Packages (Law and McComas, 2002), (Fu, 2002)

Optimization Package	**Merchant**	**Simulation Software Supported**	**Heuristic Procedures Used**
“AutoStat”	“Brooks-PRI Automation”	“AutoMod, AutoSched”	“Evolution Strategies”
“Extend Optimizer”	“Imagine That”	“Extend”	“Evolution Strategies”
“OptQuest”	“Optimization Technologies”	***“Arena***, Flexsim ED, Micro Saint, Pro-Model,QUEST,SIMUL8”	“Scatter Search, Tabu Search, Neural Networks”
“WITNESS Optimizer”	“Lanner Group”	“WITNESS”	“Simulated Annealing, Tabu Search”

CHAPTER 3

CASE STUDY FROM HOUSEHOLD GOODS INDUSTRY

In this Chapter of the Thesis, the simulation and simulation-based multi objective optimization studies on the Type-A crankshaft production line in The Refrigerator Compressor Plant, Eskişehir as a case study will be made in detail. In addition, the simulation study on the design alternatives which are casting, Type-B and Spindle Stop&Optimization will be made. For the simulation study, ARENA software of Systems Modeling Corporation will be used. For the optimization study, first of all, the simulation model prepared at the beginning of this Chapter will be used as an input for the optimization process. Then, an optimization solver named as OptQuest in the Arena software will be used for the purpose.

3.1. The Refrigerator Compressor Plant, Eskişehir- A Case Study

Climate change has threatened the nature in the global scale. It is known that the negative effects of greenhouse gases cause climate change and global warming; and CO_2 is the most important gas that contributes to the greenhouse effect. Therefore, many researches are done to minimize carbon emissions, and it is learnt that minimizing energy consumption directly leads to the minimization of carbon emissions.

Traditionally, energy has been viewed as a bill to be paid, cost, and an expense to be controlled. The majority of energy consumption and carbon footprint is from electricity that is used to light, heat, and cool buildings, and for production.

Moreover, cost is an important issue in the manufacturing sectors. *Cost minimization* is to optimize the overall cost in the system in order to make the system be sustainable. To achieve this, first of all, the cost parameters taking role in the production line are determined. Then, the overall cost estimation have been made. Cost minimization should be made without affecting the other issues adversely.

A case study has been prepared about simulation-based multi-objective optimization in the Type-A crankshaft production line in the The Refrigerator Compressor Plant in Eskişehir. It has been learnt at the beginning of the study that the problem in the Plant is the huge amount of energy consumption, the corresponding carbon emissions and the overall cost in the production stage in the life cycle of the Type-A crankshaft.

As a corporate policy, The Company started to track and reduce its ecological footprint in all of its plants and administrative buildings. The Figure 3.1 below presents its energy consumption breakdown across its plants in Turkey. The refrigerator plant in Eskişehir claims the largest consumption portion by 39,2%.

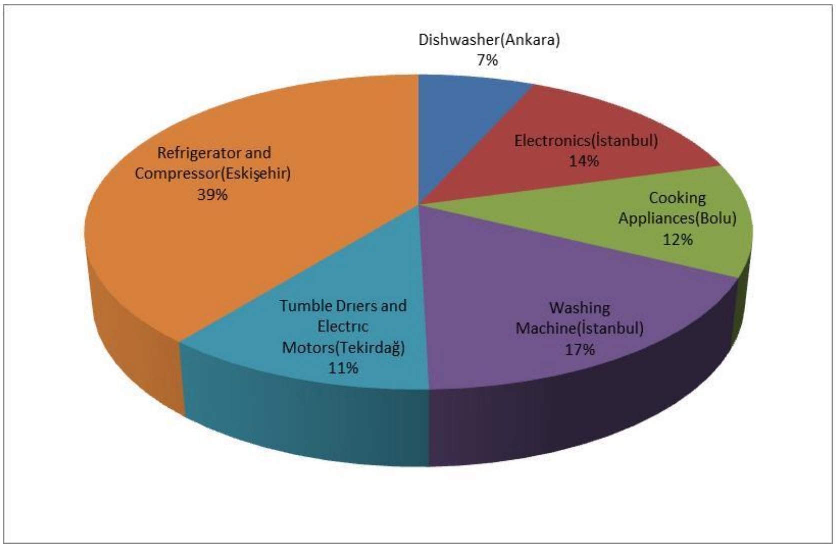

Figure 3.1 Electrical consumption by Plants (2011) (Uluer et al., 2015)

After consultations with energy and environmental affairs department in The Refrigerator Compressor Plant, the compressor plant within its refrigerator plant located in Eskişehir, was chosen to be the implementation site.

This site produces approximately 2.5 millions of refrigerator compressors annually. An assembly view of a sample Type-A compressor and the crankshaft are given in Figure 3.2. The reason of why the Type-A crankshaft is chosen for investigation and implementation will be shown later.

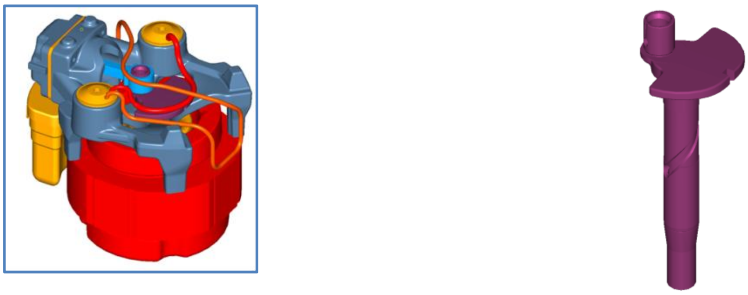

Figure 3.2 Assembly view of Type-A refrigerator compressor and the crankshaft (Uluer et al., 2015)

There is an active energy metering infrastructure at the compressor plant where data is collected with power meters called “Siemens Sentron PAC3200”. Meters installed before the case study, were mostly at the line level, providing a full visibility deeper than production-line level. Therefore energy consumed by manufacturing processes could not be segregated and broken down into its components.

Moreover, energy consumed by material handling equipment was not measured anywhere in the refrigerator compressor plant. Indirect energy consumption of some supplementary facilities were monitored which are used to estimate total indirect energy consumption.

In general, data collected from the plant was used for tracking and reporting purposes. It was not adequate for providing any insight at process level as far as automated process chains and machining operations in the factory.

In order to understand share of each component in a compressor, data collected at line level was analyzed and embodied energy of a Type-A compressor assembly was calculated.

Table 3.1 represents energy consumed by manufacturing processes for a Type-A compressor parts and some of the allocated indirect energy consumption values to facilities measured in a period of 5 months. During this measurement period 576,467 crankshafts were manufactured.

Table 3.1 Embodied energy breakdown of Type-A compressor (Uluer et al., 2015)

COMPONENT/PART	**ENERGY (%)**
Assembly	7.0
Crank	9.9
Body	11.3
Valve Plate, Piston, Connecting Rod	3.5
Rotor	5.6
Stator	4.5
Outer Shell	26.2
Supplementary facilities	16.6
R&D	4.2
HR	1.4
Non-measured	9.8
TOTAL	**100**

This preliminary investigation of the energy consumed by manufacturing processes reveals that much of the process energy is consumed by outer shell (26.2%), crankshaft (9.9%) and body (11.3%) production.

Among these three, crank line has most automation features with conveyors and transfer robots that are used for material handling between fully automated and custom made machining centers. Also it contained much high precision machining equipment, hence, for the case study of the framework, it was a good selection for deeper investigation and implementation.

In the investigation, Type-A crankshaft production line has been determined to have the huge amount of energy consumption in the machining department. Therefore, the production stage of the life cycle of a Type-A crankshaft will be focused on.

To minimize negative impacts on the surrounding, actions are prioritized on how less energy which reduces carbon emissions can be used; and simulation-based multi-objective optimization have been prepared to optimize multi objectives.

3.1.1. Brief Information About The Type-A Crankshaft Production Line

Type-A crankshaft production line in the refrigerator compressor plant is drawn in the system layout shown as below Figure 3.3. To make the layout clear, and easily understandable, the Type-A production flow under the layout has been shown.

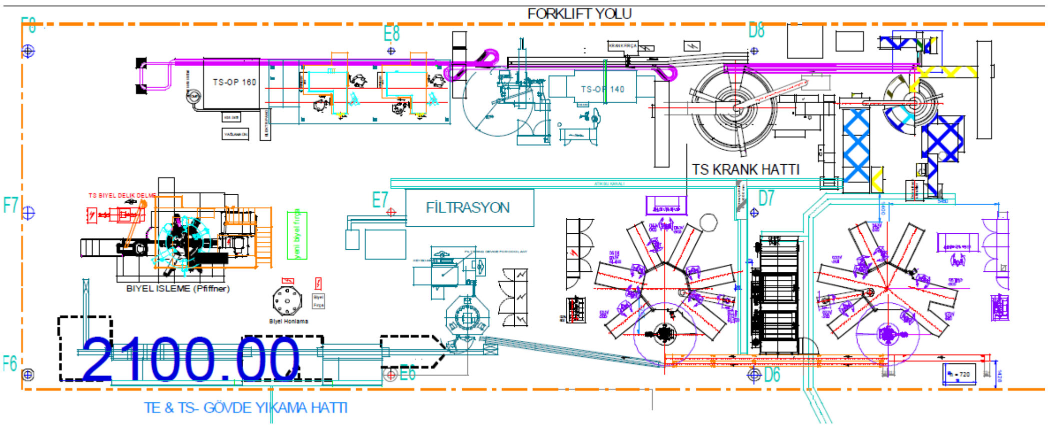

Figure 3.3 Refrigerator compressor plant layout

Type-A crankshaft has gone through some operations to turn into final product. Generally, there are seven machines in the production line such as Metal Cutting-1 which has 10 stations, Metal Cutting-2 that has 15 stations, Sand Deburring, Marking, Grinding-1 and -3 that have 2 parallel machines that are used for the same operation and Grinding-2. Production flow of Type-A crankshaft is shown in the below Figure 3.4.

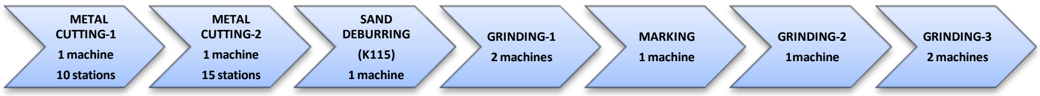

Figure 3.4 Production flow in the Type-A crankshaft production line

In the production process of the Type-A crankshaft, first of all, raw materials (parts) enter the system. Then, they come to the input area. The first conveyor changes the existing position of the part to the right position and put it in front of the fanuc robot. Fanuc robot holds two parts near the buffer area.

It puts one of them in front of the Metal Cutting-1 machine to be processed. The robot of the machine takes the part inside the machine.

After part is machined in Metal Cutting-1, the robot puts the machined part on the next conveyor (that is between Metal Cutting-1 and Metal Cutting-2 machine) and conveyor will convey the part until the part arrives at the Metal Cutting-2 machine. The robot of this machine takes the part inside the machine. Inside each machine (Metal Cutting-1 and Metal Cutting-2), a rotary table transfers parts between each station, counter clockwise. After part is machined in Metal Cutting-2, the machined parts are collected in boxes manually and then transported to the Sand Deburring machine which is a remote station.

After this process is finished, machined parts are brought onto the next conveyor manually, and then parts are machined through Grinding-1 machine, Marking, Grinding-2 and -3 machines in order to attain high tolerance of crankshaft at its certain features. After a crank is produced, the finished parts are hold as boxes. There is extra information about the Type-A crankshaft production line shown as follows:

- Sometimes, electrical and mechanical problems occur in the conveyor that is located between Metal Cutting-1 and Metal Cutting-2 machine. Problems are always recorded.
- Work-in-process parts are taken to the sanding machine after Metal Cutting-2 machine for chip removal.
- There is only one sanding machine, and it is away from the production line.
- Generally, parts are taken to the sanding machine when their numbers reach to 200 parts.
- In one step, chips of 100 parts are removed in 10 or 15 minutes.
- When the models of the crank change, their dimensions will also.
- Defect parts are caused from the molding mistakes.
- Sunday is holiday.
- In Metal Cutting-1 machine, process time is adjusted so as to get rid of waiting time and queue.
- Machine tools have spare tools. The change time of the tools changes with respect to the operators.
- Each shift is about 8 hours.
- Average of 40-50 parts is defected in one shift.
- Maintenance is made two times in a year. Production line is stopped for one week in the maintenance process.

3.1.2. About The Company

The Refrigerator Compressor Plant was founded in 1956. Headquarters are located in Ankara, Turkey. Having operations in consumer products industry with manufacturing, marketing, and after-sales services, The Plant offers products and services all around the world with its 23000 workers, and 12 production facilities in several countries all over the world.

3.1.3. History of The Company

The Refrigerator Compressor Plant was founded in 1956. They produced the first washing machine in 1970 and the first refrigerator in 1971 in Turkey. In 1976, Refrigerator Plant began productionin Eskişehir. In 1977, *Compressor Plant began production in Eskişehir*. R&D Center was established in 1992. Dishwasher Production Plant began production in 1994 in Ankara. In 2007, Refrigerator and Washing Machine Production Plant began production in Russia and Washing Machine Production Plant began operations in China.

3.1.4. Goals of The Company

The Company aims to develop and offer products that are eco-friendly, innovative in technology and design, easy to use, and prevent waste with “sustainable development” approach.

The Company integrates its "sustainability" approach to its main business operations. They assess sustainability and climate change related risks and opportunities and stakeholder expectations as its inputs.

The company assesses each factor at the beginning of the design stage of the final good for controlling the environmental effect of the finished good during its life cycle. In 2013, Plants of The Company have carried out many projects for reducing energy consumption and wastes.

In sustainable manufacturing ("Constructing a sustainably competitive Europe manufuture", 2007), manufacturing transformation process is drawn as follows:

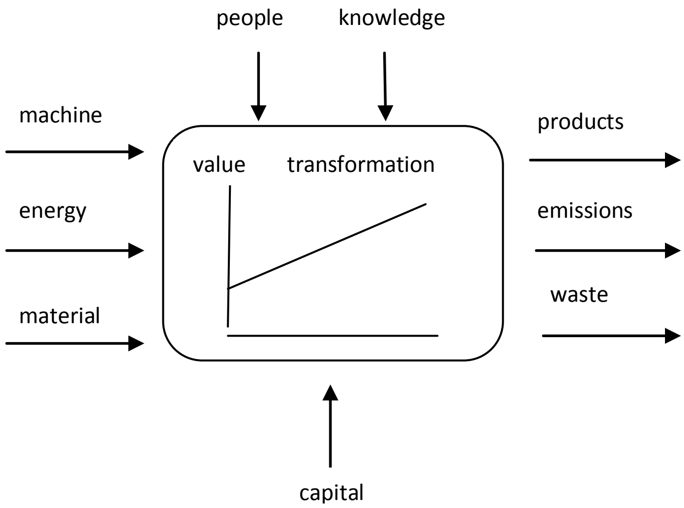

Figure 3.5 Manufacturing transformation process in sustainable manufacturing ("Constructing a sustainably competitive Europe manufuture", 2007)

It is easily seen from the Figure that manufacturing process consists of transformation of raw material into finished product that gains value. People, knowledge and capital play important role in the transformation process. Manufacturing basically utilizes machine, consumes both energy and material. At each stage in the production line, emissions and waste occur. At the end of the final stage, part will be turned into final product.

The reason of why simulation study has been made in this Thesis is that simulation easily troubleshoots the existing system. The proposed system (prototype of the adjusted system) can easily be seen, the changes in the data and in the production line integrated into the computer model can be traced and improvements will be made in the short run.

3.2. Simulation Study

According to Law et al. (1991), Simulation study consists of many steps to model the existing system. Steps are listed as follows:

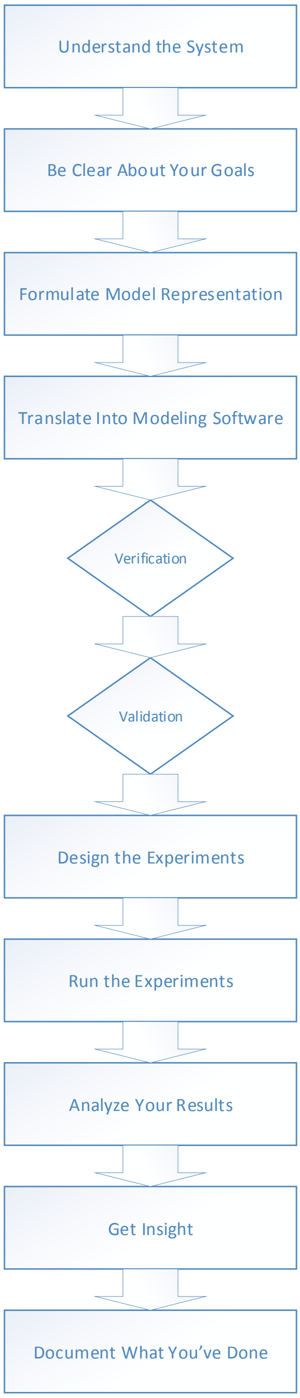

Figure 3.6 Steps in Simulation Study (Kelton et al., 2008)

Understand the System

Site visits to the refrigerator compressor plant and having contact with the people who work in the existing system on a day-to-day basis were made. The problem in the existing system was investigated after site visits.

After site visits, discussion with the qualified people in the factory and data taken from the plant, the high energy consumption problem in the Type-A crankshaft production in the refrigerator compressor plant was determined.

Be Clear About Goals

According to the problem, goal is determined to be the optimization of multi objectives such as maximization of the number of final products per shift, minimization of the amount of energy consumed and the corresponding carbon emissions, and the overall cost in the real system.

Formulate the Model Representation

Logical model and flow diagram:

In Type-A crankshaft production line, a raw material of the crankshaft is gone through the processes in sequence with spotting, turning, face machining, drilling, canalizing, sanding, grinding, marking, and grinding again to turn into finished product.

After the completion of spotting, turning, face machining, drilling, canalizing processes in *Metal Cutting-1* and *Metal Cutting-2* (which are also called as Multi Spindle) machines, parts are collected for *Sand Deburring*.

Both Metal Cutting-1 and Metal Cutting-2 machines are machines that have rotary tables making 10 and 15 processes in sequence. After parts are machined in Metal Cutting-2 machine, they do not move ahead in the conveyor line, they are taken and collected near the line for Sand Deburring operation.

When the collected parts reach up to nearly 200 parts, they are taken to the Sand Deburring machine which is away from the line, and then at the end of the sand deburring operation, parts are put on the conveyor line by operator manually.

After that, parts are moved through the Grinding-1, Marking, Grinding-2 and Grinding-3 operations. There are two parallel drilling machines operating in Grinding-1 and Grinding-3 machines and parts move through one of the parallel machines to complete the stages. Parts are transferred with the help of conveyors between machines and robots put parts into the machines. All machines are open for 24 hours and also in shifts when machines are not used actively.

Assumptions and simplifications:

During the system analysis, it has been seen that conveyors have a duty of buffer place. Therefore, they have not been placed as Conveyor modules in simulation model. Besides, machines do not waste time for waiting following part comes from the conveyor. Therefore, the distances and velocities of the conveyor have not been added into the simulation model.

Data Analysis:

The list of the data collected for the simulation model is shown as the following:

Model inputs:

DES (Discrete Event Simulation) model receives input related to process parameters and generates operational and consumption variables. For the automated process chains, model inputs that are used are listed as the following:

- Operation times,
- Robot transportation times,
- Labor shift schedule,
- Machine shift schedule,
- The breakdown frequencies and times of machines,

- The setup frequencies of machines (the model and diameter change of the machined part oriented),
- The setup times of all machines ,
- Mean time between failures,
- Failure duration, and $E_{theoretical}$

The data collected for the verification analysis:

- Cycle times of all machines,
- The amount of machined parts per shift,
- The time between to successive parts exit from the system

The simulation will yield the following outputs:

- Number of parts produced per shift (Objective-1),
- Idle time of each machine,
- E_{aux} per machine,
- E_{aux} per part (Objective-2),
- WIP,
- Waiting times in queue,
- Machine utilization.

Translate Into Modeling Software

The processes in the existing system are ranked as System Entrance, Multi-Spindles which are Metal Cutting-1 and Metal Cutting-2, Sand Deburring, Grinding-1 (there are two parallel machines), Marking, Grinding-2, Grinding-3 (there are two parallel machines), and System Exit.

Modules in the System:

Create Module:

"*Create*" module is a starting point for entities in a simulation model. First, entities are created using a schedule or based on a time between arrivals. Then, they leave the module to begin processing through the system.

Seize Module:

The "*Seize"* module can allocate units of one or more resources to an entity. They may be used to seize units of a resource as defined by an alternative method like an attribute or expression. When an entity enters this module, it will wait in a queue until all specified resources are available at the same time.

Decide Module:

The "*Decide"* module is used for allowing for decision-making processes in the system. It includes options for making decisions based on conditions, or probabilities. Conditions can be based on attribute values, variable values, and the entity type or an expression.

Separate Module:

"Separate" modules can either copy an incoming entity into multiple entities or split a previously batched entity. Rules for allocating costs and times to duplicate, and for attribute assignment to member entities are specified in this module.

When splitting existing batches, the temporary representative entity formed is disposed and the original entities formed the group are recovered. The entities progress sequentially from the module in the same order where they originally were added to the batch.

When duplicating entities, the particular number of copies is made and sent from this module. The original incoming entity leaves the module as well.

Process Module:

"Process" modules show the main processing method made by machines, stations, e.t.c. in the simulation. There are options for seizing and releasing resource constraints in this module. In addition, there is an option for using a "submodel" and specify hierarchical user-defined logic.

The process time is allocated to the entity and determined to be "value added, non-value added, transfer, wait or other". The associated cost will be added into the appropriate category.

Assign Module:

The "*Assign*" module is used for assigning new values to variables, entity types, entity attributes, entity pictures, or other system variables. Multiple assignments can be made with using a single Assign module.

Delay Module:

A "*Delay*" module delays an entity by a particular amount of time. When an entity arrives at this module, the time delay expression will be evaluated and the entity will remain in the module for the resulting time period. The time is then allocated to the entity's value added, non-value added, wait, transfer, or other time.

Signal Module:

"*Signal*" modules are used to show that the related process has finished. They will send signal values to Hold modules (set to "Wait for Signal", when Signal module is to be used) and release the maximum specified number of entities. When an entity arrives at this module, the signal is evaluated and the signal code sent.

At this time, entities at Hold module that waits for the signal are removed from their queues. The entity sending the signal will continue processing until it encounters a delay, enters a queue, or is disposed.

Hold Module:

The "*Hold*" module will hold an entity in a queue to either wait for a signal, wait for a particular condition to be true or be held infinitely (to later be removed with the *Remove* module).

If the entity is holding for a signal, this module is used to allow the entity to move on to the next module. If the entity is holding for a given condition to be true, the entity will remain at the module until the given condition becomes true. When the entity is in an infinite hold, the *Remove* module is used for allowing the entity to continue processing.

Release Module:

The "*Release*" module releases units of resources which an entity previously has seized. It may be used to release individual resources or resources within a set. The name and quantity to release should be specified for each resource to be released.

Record Module:

"*Record*" module collects statistics in the simulation model. Several observational statistics are available that includes time between exits through the module, entity statistics such as time and costing, e.t.c.

Sub Models:

The processes mentioned in the previous pages are located as sub models in Arena shown in Appendix A. The functions in the Sub Models are discussed as follows:

The system model starts with a Create module named as "RAW MATERIAL". This module is excluded in the first Sub model, System Entrance. Because, Sub models cannot start with a Create module due to that it has a single-sided connection line.

System Entrance Sub Model:

Arena model starts with the "System Entrance" sub model after "RAW MATERIAL" Create module. This sub model has functions between the entrance of the crankshaft to the production line and taking the crankshaft in front of the first machine (Metal Cutting-1).

The time of the shift is set to 8 hours. In this Sub Model, only one "*Seize*" module is used. In this module, a resource called "*fanucBuffer*" is used. "fanucBuffer" will hold the area for the next crankshaft. This activity is a non-value added activity, so that seize allocation is selected to be non-value added.

The "*Decide"* module has a function of that if the number of parts in the queue reaches up to 30 or less, crankshaft will move through the next module ("*Separate*" module). Otherwise, it will be arranged in front of the first machine by fanuc robot. The time of this process is set to be 2 seconds which is determined according to the observations and the information taken from the refrigerator compressor plant in The.

"*Separate*" module will split the incoming batched entities at the beginning of the production line. Then, *fanucRobot* will arrange the crankshaft in front of the first machine, Metal Cutting-1.

Multi-Spindle (Metal Cutting-1) Sub Model:

Which part is arranged on the line will be tracked with the help of "*Assign*" module in the simulation model. "*Delay*" modules are used to show the robots' go-back times and rotation of the rotary tables and the duration passed within these actions.

In order to show that the process has finished, "*Signal*" modules are used in the system model. In order to get the signal, "*Hold*" modules are used and module type is written as "Wait for Signal" in the simulation model.

When the entity such as crankshaft enters the "*Release"* module, it will give up tracking of the particular resource(s). Any entity waiting in queue for those resources will gain control of the resources immediately.

The "*Process"*module is filled by the same principle for all of the stations. After part is machined, a signal will be created. Then, "*Hold*" module will wait for this signal. After signal is taken, robot will make the part catch up with the next station in Metal Cutting-1.

These steps are available for the other stations in the machine. The "*Record"* module which is named as "Metal Cutting-1*BetweenExits*" shows the time between two consecutive exits in Metal Cutting-1 machine in the existing system.

<u>Rotary Table Mechanism in the Metal Cutting-1 Sub Model:</u>

Rotary table mechanisms of these machines show the activities of stations (10 stations in Metal Cutting-1 machine, 15 stations in Metal Cutting-2 machine) made on these machines at their cycle times. First station is the loading-unloading station on the rotary table.

For each station, signal is created by "*Create*" module called "*create first rotation signal*". To determine which station the next part will go through, a "*Decide*" module is used. Then, stations wait for their own signals to process the part with "*Hold*" module. The same principle is taken for the other stations in Metal Cutting-1

<u>Multi-Spindle (Metal Cutting-2) Sub Model</u>:

Metal Cutting-2 functions and their modules are prepared with the same principle in Metal Cutting-1 machine. The mechanism in Metal Cutting-2 will be summarized as follows:

At the beginning of the machine, top robot grasps the part and takes it to the machine. Then, the "*Signal*" module used next shows that the part has been arranged on the Metal Cutting-2 entrance. At the same time, station-1 will wait for its signal with the "*Hold*" module.

Then, the station takes the signal. After that, the rotary table is rotated with using a "*Delay*" module. And the second station process will be made (station-1 is the station where only loading and unloading processes are made). After the other stations operate, the number of parts which exit the Metal Cutting-2 is traced at the end of this Multi-Spindle Sub model and recorded with the help of "*Record*" module.

<u>Rotary Table Mechanism in the Metal Cutting-2 Sub Model:</u>

Rotary table mechanisms of these machines show the activities of stations (10 stations in Metal Cutting-1 machine, 15 stations in Metal Cutting-2 machine) made on these machines at their cycle times.

This rotary table mechanism is summarized as follows: For the first rotation, Metal Cutting-2 signal is created with "*Create*" module. With the help of "*Decide*" module, which signal will be given is to be decided in "*which signal Metal Cutting-2*" module. In addition, each station will wait for its own signal. Then, a new Decide module is created in order to rotate the rotary table again.

<u>Sand Deburring Sub Model:</u>

Parts are collected until the required amount of them is reached. When the amount reaches to the required amount, parts will be taken to the sand deburring. The parts machined and come back from the sand deburring are put onto the conveyor. In order to understand whether the part reaches to the required amount or not, the waiting mechanism is proposed for this sand deburring machine.

Waiting Mechanism in Sand Deburring Sub Model:

Aim of this mechanism is to be aware and noticed that the parts batched for deburring have reached up to required number.

Grinding-1 Sub Model:

The functions made in Grinding-1 are discussed as follows:

In Grinding-1, there are two parallel machines operate at the same time. Therefore, a "*Decide*" module should be used to determine which machine the next part will go through. After decision through which machine the next part will move, top robot takes the part on the conveyor to put on one of the parallel machines to operate. At the same time, Grinder will hold the area for part to be processed.

When part is arranged onto the Grinder, process will be made. The "Process" module is filled up with the same principle for First Parallel Machine in Grinding-1 and Second Parallel Machine in Grinding-1.

After the part has been machined, the top robot will take the machined part and put onto the conveyor for the next machine which is called "Marking Machine".

Marking Sub Model:

Marking process is done in this Sub model. The related modules utilized are discussed as follows:

First of all, top robot-4 grasps the part on the conveyor. Then, it will take the part to the marking machine. After that, marking process is done with the help of "*Process*" module. After process has finished, top robot-4 grasps the machined part in front of the marking machine and takes it to the next machine (Grinding-2). Finally, top robot-4 will be released by a "*Release*" module.

Grinding-2 Sub Model:

The modules used to show the sequences of the steps in this grinding process are similar to First Parallel Machine in Grinding-1 and Second Parallel Machine in Grinding-1. Difference from the Grinding-1 that have two parallel machines operate at the same time is that there is only one machine operates in this machine. The functions made by the Grinding-2 Sub model are discussed as the following:

First of all, top robot takesthe part on the conveyor and to the machine to be machined. Then Grinder holds the area for machining part with "*Seize*" module.

After that, part is arranged on the machine with "*Delay*" module. Then, part will be machined in the machine with the help of "*Process*" module.

After machining operation, top robot takes the machined part in front of the machine with "*Seize*" module. Then, part will be put on the conveyor. At the end of the Sub model, number of parts exit the Sub model will be traced.

Grinding-3 Sub Model:

In Grinding-3, there are two parallel machines operate at the same time. Therefore, a "*Decide*" module should be used to determine which machine the next part will go through. After the decision of which machine the part will go through for process, top robot takes the part from the conveyor and to the one of the paralel machines. Then, Grinder will hold the part to be machined.

"*Delay*" module has been used to show the operation of that part is arranged on the machine. Machining operation will be made with using a "*Process*" model. After that, top robot takes the machined crankshaft from the machine using a "*Seize*" module.

Besides, it will put it on the conveyor. At the end of the Sub model, the number of parts exit from the Sub model will be traced and reported after simulation run.

System Exit Sub Model:

The "*Record*" module named as "*sum the time between exits*" is used to record the summation of the time between exits. The parts that exit the system are shown in this sub model. In the "*Assign*" module, total parts machined and exit the system are count to be aware of how many crankshafts are produced within a given period of time.

"*Dispose*" module is taken into account as the ending point for entities in a simulation model. Entity statistics are generally recorded before the entity such as "FINISHED PART" is disposed in the system model.

Conceptual design:

In order to implement the system model in Arena, relevant data types which are the pieces of the simulation model have to be identified first. Required data types are written as follows:

1. Entities like products
2. Attributes like product and processing data
3. Activities and events of the simulation model like processes (e.g. marking,…)
4. Queues like buffers
5. Resource like equipments (operator, robot)
6. Variables like energy consumption by processes
7. Measures of effectiveness

1. Entities:

Entities are the dynamic objects moving around, changing status, affecting and are being affected by other entities and the state of the system, and affecting the output performance measures. They are created, move within the system, and then are disposed when they leave. Entities are listed in the below Table 3.2.

Table 3.2 Entity Module

Entity Type:
Crankshaft
Metal Cutting-1 rotation
Metal Cutting-2 rotation

There are two types of entities called as “external and internal entities” (Schriber 2001). “External entities” are entities whose creation and movement are explicitly arranged by the modeler such as the crankshafts to be processed in the model. They are created when they arrive at the system, move through the queue if exists, are served by the machines, and then are disposed of as they leave.

Unlike the external entities, “internal entities” are created and manipulated implicitly by the simulation software itself or designed by the modeler to pay attention to certain modeling operations. They may be used to account for logic operations within the system like changing the state of a resource at some certain time.

Most of the programming effort required to account for logic operations using these type of entities in simulation, has been transferred into simulation packages with the use of advanced simulation tools. Specially adapted built-in modeling constructs used in Arena software such as “Failure and Schedule”, are examples to internal entity creating modules. Failure and Schedule Modules are shown as the below Table 3.4 and Table 3.3. The detailed information about these modules is discussed in the following:

"Schedule" Module:

This model defines an operating schedule for a source when it is used in conjunction with Resource module. On the other hand, it defines an arrival schedule when it is used in conjunction with the Create module. Schedule can also be used to factor time delays based on the simulation time.

Table 3.3 Schedule Module

NAME	TYPE	TIME UNITS	DURATIONS
shiftSchedOperator	Capacity	Minutes	129 rows
Metal Cutting-1ShiftSchedOperator	Capacity	Minutes	135 rows
shiftSchedMachine	Capacity	Hours	1 row
Grinding3-2ShiftSchedOperator	Capacity	Minutes	93 rows
Grinding2ShiftSchedOperator	Capacity	Hours	4 rows

"Failure" Module:

This module is designed to be used with resources. When a failure occurs, the overall resource is failed in the model. Failures are used with single- or multiple-capacity resources whose individual resource units all fail at the same time.

In "*Failure*" Project Bar, the up time and down time values and count values for tool changes will be seen in the existing system. For example, according to "Metal Cutting-1ToolChange", count value is 900, and down time is 1464 seconds. It means that after each 900 parts, Metal Cutting-1 will be stopped for 1464 seconds.

According to "MachineFailure", the uptime and downtime values will be seen. For example, in "Metal Cutting-1Failure", uptime value is 1.08 days and downtime value is 42 minutes. It means that Metal Cutting-1 will fail within 1.08 days and stop for 42 minutes.

Finally, the diameter and model rotations for Metal Cutting-1 and Metal Cutting-2 and their uptime and downtime values will be seen. For example, Metal Cutting-1 diameter rotation uptime value is 72 hours and downtime value is 1 hours. It means that Metal Cutting-1 has a diameter rotation after 72 hours working, and stop for 1 hour until rotation will finish. According to model rotations, the principle is the same.

Table 3.4 Failure Module

NAME	TYPE	UP TIME	UP TIME UNITS	COUNT	DOWN TIME	DOWN TIME UNITS
Metal Cutting-1Failure	time	1.08	days		42	minutes
Metal Cutting-2 Failure	time	1.48	days		38.60	minutes
First Parallel Machine in Grinding-1 Failure	time	5.74	days		38.48	minutes
Second Parallel Machine in Grinding-1 Failure	time	1.0	days		0	minutes
Grinding-2 Failure	time	5.74	days		62.39	minutes
First Parallel Machine in Grinding-3 Failure	time	5.50	days		63.96	minutes
Second Parallel Machine in Grinding-3 Failure	time	4.26	days		28.87	minutes
Metal Cutting-1ToolChange	count			900	1464	seconds
Metal Cutting-2 ToolChange	count			1000	910	seconds
First Parallel Machine in Grinding-1 ToolChange	count			3000	660	seconds
Second Parallel Machine in Grinding-1 ToolChange	count			3000	660	seconds
Grinding-2 ToolChange	count			20	12.5	seconds
First Parallel Machine in Grinding-3 ToolChange	count			10	13	seconds
Second Parallel Machine in Grinding-3 ToolChange	count			50	56	seconds
Metal Cutting-1DiameterRotation	time	72	hours		1	hours
Metal Cutting-1ModelRotation	time	19.5	hours		0.25	hours
Metal Cutting-2DiameterRotation	time	72	hours		0.5	hours
Metal Cutting-2ModelRotation	time	19.5	hours		0.25	hours

2. Attributes:

Entities retrieve their unique identities with the attached attributes into them. An attribute is a common characteristic of the same type of entities with different values assigned they can differ from one entity to another, that distinguishes from one entity of a type to another. These assigned values of attributes provide the basis to estimate statistics and offer programming flexibilities for the modeler.

The most important thing about attributes is that their values are tied to particular entities in simulation. These values can be assigned to entities at the beginning of a run, or they can be assigned at special times during the run.

The assigned values for attributes are subjected to changes as the simulation run proceeds and these values can be used at any time during the run or after the simulation run completed. The attributes of the Type-A crankshaft are listed in the Table 3.5 below.

Table 3.5 Attribute Module

NAME
topHeld
no
partinwhichOrder
Metal Cutting-2idleBeginning

3. Activities and Events:

Activities are the processes specified in the simulated system. Entities that engages with the activities compose *events* and this cause changes in the state of the system. There are three types of activities which are delays, queues and logic.

Delays are due to the detaining of the entities for a definite amount of time in the system. The length of the waiting time is either fixed or randomly generated by using statistical distributions. The events related to a delay occur at the beginning and the end of the delay where the entity arrives at and leaves the delay block.

In the existing system, delays occur because of the processes defined in the system and the transferring of entities from one station to another (robot loading and unloading). Robot loading and unloading delay is treated as a constant value, whereas the cutting times are different from one station to another.

4. Queue:

When an entity cannot move on, because it may need to seize a unit of a resource that is tied up by another entity, a place to wait, which is the purpose of a *Queue*. Queues make the entities wait in the system as well but the difference from delays is that the waiting period is unknown in advance.

Waiting in queues occurs in either to seize for a resource, or for a system condition to occur such as storing the parts to be taken out of the queue when the right conditions exist. Queue module can be used for changing the ranking rule for a particular queue.

The ranking rule is set as “First In First Out” for all queues unless elsewise specified in this module. Queues have capacities representing a limited buffer.

Logic activities allow the entities to help make decisions for following defined routes in the system. By interacting with the system-state and user-defined variables and attributes, lots of logic operations can be realized.

Everything is centered around *events* in simulation. An event is a thing happening at an instant of time that might change attributes, variables, e.t.c.

5. Resources:

Resources reflect service providers with limited capacity for whom the entities compete with each other in simulation. In addition, resources include costing information and resource availability.

Resource failures and states can also be referenced in this module using Advanced Process and Advanced Transfer Panels. An entity can seize more than one resource at a time, for instance, a part seizes both a machine and an operator at the same time. In addition, a single resource can reflect a group of several individual servers and serve many entities.

For example, a machine or an area can have a capacity of more than one. Resources may have a fixed capacity which does not vary over the simulation run or may operate based on a schedule.

Resources utilized in the production line are listed as the following:

– top robots of each machine,
– fanucBuffer,
– fanuc robot,
– each station on Metal Cutting-1 rotary table,
– each station on Metal Cutting-2 rotary table,
– grinding machines,
– marking machine,
– sand deburring machine,
– Metal Cutting-1 and Metal Cutting-2 table,
– Metal Cutting-1 and Metal Cutting-2 entrance,
– operators of each machine, and
– grinder areas.

All the resources have a fixed capacity of one except the sixth top robot. It has a capacity of two that means it can carry two parts at the same time. Besides, operators of each machine are based on the schedule, not have a fixed capacity.

6. Variables:

Variables store information reflecting system characteristics in simulation. They are used to monitor anything to the entire simulation. Users can reference their variables in other modules, reassign new values to variables with the Assign module, and use them in any expression. Variables' values are assigned by using a file, and the values are specified manually in the "*Variable*" module.

Parameters used in Arena Simulation Model in order to estimate the auxiliary energy of Type-A are shown in "*Variable*" Project Bar (in Basic Process Panel) as follows:

– cutting times in all stations (10 stations) in Metal Cutting-1,
– cutting times in all stations (15 stations) in Metal Cutting-2,
– robots (in front of Metal Cutting-1 and Metal Cutting-2)go and back time,
– number of parts that are going to sand deburring machine,
– cutting times in all grinding machines (Grinder-1, Grinder-2 and Grinder-3),
– robots (in front of each grinding and marking machine) go and back time,
– cutting time of marking machine,
– rotary table rotation time,
– number of shift, duration of each shift,
– grinder arrangement time, and
– powers consumed to estimate E_aux of each machine.

Parameters used in Arena Simulation Model in order to estimate the overall cost of Type-A crankshaft per shift are shown in "*Variable*" Project Bar (in Basic Process Panel) as follows:

- Investment Cost,
- Energy Cost,
- Direct Labor Cost,
- Indirect Labor Cost,
- Total Material Cost.

These parameters have been determined after making discussion with the qualified people in The Refrigerator Compressor Facility.

Investment Cost:

The data required to estimate the investment cost in the Type-A crankshaft production line are cost per each machine and investment year per each machine. The values of these parameters are assumed because of privacy policy in the Company.

Energy Cost:

Energy Cost is assumed after observation on the production line because of the privacy policy in the Company.

Direct Labor Cost:

In order to estimate the Indirect Labor Cost, the required data are the labor salary, the number of labors working in the line, and the working hours of labors in the line. The values of these parameters are assumed because of the Company privacy policies. It is known that direct labor cost is estimated per crankshaft per shift.

Indirect Labor Cost:

Indirect Labor Cost includes the maintenance operator not working in production and the quality assurance operators, e.t.c. These operators cost will not affect the overall cost in the production line, therefore, they are not taken into consideration, and are ignored.

Total Material Cost:

Total Material Cost includes the materials bought for production, raw materials, e.t.c.

Energy Values:

Energy values include direct energy that consists of auxiliary and theoretical, and the indirect energy (Rahimifard, 2009). *Direct Energy* (theoretical+ auxiliary) is the energy required by a process the energy consumed by activities that are required to manufacture a component.

Auxiliary Energy is required by backing up activities to carry out the process (e,g. control system, lubricants, coolant, …) Auxiliary energy is taken from the stations.

Theoretical energy consists of geometric and manufacturing parameters (V_{rem} and k_c), and the theoretical energy can be calculated by multiplying these two parameters. *Theoretical Energy* is the calculated minimum energy required to carry out a process.The theoretical energy data taken from the Features are shown in Appendix B. In the Features Table in Appendix B, the geometric and manufacturing parameters which are used to calculate the theoretical energies and CO_2 of the Features will be seen. Each Feature includes more than one machine in the production line. *Indirect Energy* is the overhead energy required by a manufacturing environment in which the process is carried out (e.g. lighting, heating, e.t.c.). The energy formulations used for each type of process including metal cutting, grinding, deburring and handling, are shown in the below Table 3.6.

Table 3.6 Energy formulation of the process chain (Uluer et al., 2015)

Process	$\mathbf{E}_{\mathbf{theoretical}}$	$\mathbf{E}_{\mathbf{aux}}$	**Auxiliary Energy Formula**
Metal Cutting	$V_{rem} * k_c$	$E_{StACaux}+ E_{tableACaux}+ E_{Imorotaux}+ E_{tableservoaux}+ E_{StServoaux}+ E_{Filtaux}+ E_{Chillaux}$	$E_{StACaux} = P_{stACaux} * t_{cycle} + P_{StACauxcons} * t_{ch} + P_{StACauxcons} * t_{idle}$
			$E_{tableACaux} = E_{tableACaux} + P_{tableACauxcons} *(t_{ch} + t_{idle})$
			$E_{Imorotaux} = P_{imorotaux} * t_{cycle} + P_{imorotauxconstant} * (t_{ch} + t_{idle})$
			$E_{tableservoaux} = P_{tableservoauxvar} * t_{table} + P_{tableservoauxcons} * (t_{cycle} + t_{ch} + t_{idle})$
			$E_{StServoaux} = P_{stServoauxvar} * t_c + P_{stSevoauxcons} * (t_{cycle} + t_{ch} + t_{idle})$
			$E_{Filtaux} = P_{Filtaux} * t_{cycle} + P_{Filtauxconst} * (t_{ch} + t_{idle})$
			$E_{Chillaux} = P_{Chillaux} * t_{cycle} + P_{Chillauxconst} * (t_{ch} + t_{idle})$
Grinding	$V_{rem} * k_c$		$(P_{grindingaux} + P_{filtaux} + P_{pumpaux}) * t_{cycle} + (P_{grindingauxcons} + P_{filtauxcons}) * t_{idle}$
Sand Deburring	$P_{av} * t_{deburring} / n_{batch}$		

In the Table 3.6 above, the energy formulation of the process chain in the Type-A production line is written. The processes are classified as Metal Cutting, Grinding, Sand Deburring.

Metal cutting operation includes Metal Cutting-1 and Metal Cutting-2 machines (called as Multi-Spindles). Metal Cutting-1 has 7 different auxiliary units and 10 spindle stations on a rotary table. Metal Cutting-2 has also 7 different auxiliary units and 15 spindle stations on a rotary table.

Auxiliary units can be listed as follows:

- Auxiliary energy of AC motors at each station ($E_{StACaux}$),
- Auxiliary energy of rotary table AC motors ($E_{tableACaux}$),
- Auxiliary energy of Imorotstep motors at each station ($E_{Imorotaux}$),
- Auxiliary energy of rotary table servo motors ($E_{tableservoaux}$),
- Auxiliary energy of feed servos at each station ($E_{StServoaux}$),
- Auxiliary energy of cutting fluid circulation system and filtering ($E_{Filtaux}$), and
- Auxiliary energy of chillers ($E_{Chillaux}$).

The required powers which are used to calculate the auxiliary energy mentioned above are listed as the following:

- Auxiliary power of AC motors at each station ($P_{stACaux}$),
- Auxiliary constant power of AC motors at each station ($P_{StACauxcons}$),
- Auxiliary constant power of rotary table AC motors ($P_{tableACauxcons}$),
- Auxiliary power of Imorotstep motors at each station ($P_{imorotaux}$),
- Auxiliary constant power of Imorotstep motors at each station ($P_{imorotauxconstant}$),
- Auxiliary variable power of rotary table servo motors ($P_{tableservoauxvar}$),
- Auxiliary constant power of rotary table servo motors ($P_{tableservoauxcons}$),
- Auxiliary variable power of feed servos at each station ($P_{stServoauxvar}$),
- Auxiliary constant power of feed servos at each station ($P_{stSevoauxcons}$),
- Auxiliary power of cutting fluid circulation system and filtering ($P_{Filtaux}$),
- Auxiliary constant power of cutting fluid circulation system and filtering ($P_{Filtauxconst}$),
- Auxiliary power of chillers ($P_{Chillaux}$),
- Auxiliary constant power of chillers ($P_{Chillauxconst}$)

In order to calculate auxiliary energy from power rating of each unit, the required time variables are listed as the following:

- cycle time at each spindle (t_c),
- table rotation time from one station to another (t_{table}),
- cycle time of a part in the machining center (t_{cycle}),
- waiting time of each unit for each spindle (t_{wait}), and
- idle time of machining center (t_{idle}).

Grinding operation consists of Grinding-1 which includes two paralel machines, Grinding-2 and Grinding-3 which have two paralel machines. In order to calculate the auxiliary energy consumption within the Grinding operations, the required power variables are listed as follows:

- auxiliary grinding power ($P_{grindingaux}$),
- auxiliary filter power ($P_{filtaux}$),
- auxiliary pump power ($P_{pumpaux}$),
- auxiliary constant grinding power ($P_{grindingauxcons}$), and
- auxiliary constant filter power ($P_{filtauxcons}$)

Sand Deburring operation consists of only sand deburring activities made far away from the production line. In order to calculate the sand deburring energy consumption, average power (P_{av}), deburring time ($t_{deburring}$), and batch number (n_{batch}) are needed.

Statistic:

The "*Statistic"* module defines additional statistics for collecting during simulation and specifying output files as well.While summary statistics are automatically generated for each statistic, if an output file is specified, each observation is written to here.

The types of statistics defined in the Statistics module are “time-persistent, tally (observational data), count-based, output, and frequency-based”. Data cannot be written to an output file for time-persistent and frequency statistics if users define a collection period other than the length of the entire replication. Some of the parameters written in the Statistic module are displayed in Table 3.7.

Table 3.7 “Statistic” Module

NAME	EXPRESSION
First Parallel Machine in Grinding-1 processNumber_	First Parallel Machine in Grinding-1 processNumber/18
Second Parallel Machine in Grinding-1 processNumber_	Second Parallel Machine in Grinding-1 processNumber/18
Grinding-1processNumber_	Grinding-2processNumber/18
First Parallel Machine in Grinding-3 processNumber_	First Parallel Machine in Grinding-3 processNumber/18
Second Parallel Machine in Grinding-3 processNumber_	Second Parallel Machine in Grinding-3 processNumber/18

7. Measure of Effectiveness (Performance Measures):

Performance measures are the outputs taken in the simulation run. Performance measures are used to compare alternatives with each other. Some of the performance measures are as follows:

- average waiting time of parts in queue,
- maximum waiting time of parts in queue,
- maximum number of parts in queue,
- utilization of the machine

“Expression” Module:

An expression can contain any Arena-supported expression logic, consisting of real values, Arena distributions, Arena- or user-defined system variables, and combinations of these. Expressions can be single elements or one- or 2-D arrays. Users can define expression values within the “*Expression*” module, or they can use this module to define a file from which to get expression values.

The file helps users to read expression values from an outside source. To use the expressions that have been created, reference them in the model using their name. In “*Expression*” (in the Advance Process Panel) Project Bar, users will see the things that users want to estimate in the model such as the following:

- process rates of parallel grinding machines
- idle times of each machine,
- cycle times of each machine,
- tool-change times of Metal Cutting-1 and Metal Cutting-2,
- auxiliary energy formulations for each machine
- cost formulations

Formulations in “Expression” Project Bar are written as follows:

<u>Auxiliary energy formulations:</u>

Energy formulations displayed in Table 3.6 are listed in this section again. The numbers in paranthesis show the station numbers in Metal Cutting-1 and Metal Cutting-2. In order to calculate the auxiliary energies in Metal Cutting-1 operations, and Metal Cutting-2 operations, the auxiliary energy formulas will be repeated for each station (10 stations for Metal Cutting-1, 15 stations for Metal Cutting-2) such as in the following Tables. Then, the results taken from each station will be added to show the total auxiliary energy of that machine.

The view of the energy formulations in simulation model are listed as follows:

–E_StAC_aux Metal Cutting-2=P_StAC_aux_ Metal Cutting-2 (1)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (1)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (1)*t_idle Metal Cutting-2

Table 3.8 Formulation for E_StAC_aux Metal Cutting-2 in “Expression” Module

	EXPRESSION VALUES
1	P_StAC_aux_ Metal Cutting-2 (1)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (1)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (1)*t_idle Metal Cutting-2
2	P_StAC_aux_ Metal Cutting-2 (2)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (2)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (2)*t_idle Metal Cutting-2
3	P_StAC_aux_ Metal Cutting-2 (3)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (3)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (3)*t_idle Metal Cutting-2
4	P_StAC_aux_ Metal Cutting-2 (4)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (4)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (4)*t_idle Metal Cutting-2
5	P_StAC_aux_ Metal Cutting-2 (5)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (5)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (5)*t_idle Metal Cutting-2
6	P_StAC_aux_ Metal Cutting-2 (6)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (6)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (6)*t_idle Metal Cutting-2
7	P_StAC_aux_ Metal Cutting-2 (7)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (7)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (7)*t_idle Metal Cutting-2
8	P_StAC_aux_ Metal Cutting-2 (8)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (8)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (8)*t_idle Metal Cutting-2
9	P_StAC_aux_ Metal Cutting-2 (9)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (9)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (9)*t_idle Metal Cutting-2
10	P_StAC_aux_ Metal Cutting-2 (10)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (10)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (10)*t_idle Metal Cutting-2
11	P_StAC_aux_ Metal Cutting-2 (11)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (11)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (11)*t_idle Metal Cutting-2
12	P_StAC_aux_ Metal Cutting-2 (12)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (12)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (12)*t_idle Metal Cutting-2
13	P_StAC_aux_ Metal Cutting-2 (13)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (13)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (13)*t_idle Metal Cutting-2
14	P_StAC_aux_ Metal Cutting-2 (14)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (14)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (14)*t_idle Metal Cutting-2
15	P_StAC_aux_ Metal Cutting-2 (15)*t_cycle Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (15)*t_ch Metal Cutting-2+P_StAC_aux_cons_ Metal Cutting-2 (15)*t_idle Metal Cutting-2

– E_tableservo_aux Metal Cutting-2=P_tableservo_aux_var_ Metal Cutting-2 (1)*rotary2backTime+P_tableservo_aux_cons_ Metal Cutting-2 (1)*t_cycle Metal Cutting-2+P_tableservo_aux_cons_ Metal Cutting-2 (1)*t_ch Metal Cutting-2+P_tableservo_aux_cons_ Metal Cutting-2 (1)*t_idle Metal Cutting-2

– E_StServo_aux_ Metal Cutting-2= P_StServo_aux_var_ Metal Cutting-2 (1)*rotary2st1Time+P_StServo_aux_cons_ Metal Cutting-2 (1)*t_cycle Metal Cutting-2+P_StServo_aux_cons_ Metal Cutting-2 (1)*t_ch Metal Cutting-2+P_StServo_aux_cons_ Metal Cutting-2 (1)*t_idle Metal Cutting-2

– E_ Metal Cutting-1_Filt_aux Metal Cutting-2= P_ Metal Cutting-2_Filt_aux(1)* t_cycle Metal Cutting-2+ P_ Metal Cutting-2_Filt_aux_cons(1)* t_ch Metal Cutting-2+ P_ Metal Cutting-2_Filt_aux_cons(1)* t_idle Metal Cutting-2
– E_ Metal Cutting-1_Chill_aux Metal Cutting-2= P_ Metal Cutting-2_Chill_aux(1)* t_cycle Metal Cutting-2+ P_ Metal Cutting-2_Chill_aux_cons(1)* t_ch Metal Cutting-2+ P_ Metal Cutting-2_Chill_aux_cons(1)* t_idle Metal Cutting-2
– E_StAC_aux Metal Cutting-1= P_StAC_aux_ Metal Cutting-1 (1)*t_cycle Metal Cutting-1+ P_StAC_aux_cons_ Metal Cutting-1 (1)* t_ch Metal Cutting-1+P_StAC_aux_cons_ Metal Cutting-1 (1)* t_idle Metal Cutting-1

Table 3.9 Formulation for E_StAC_aux Metal Cutting-1 in “Expression” Module

	EXPRESSION VALUES
1	P_StAC_aux_Metal Cutting-1(1)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(1)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(1)*t_idle Metal Cutting-1
2	P_StAC_aux_Metal Cutting-1(2)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(2)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(2)*t_idle Metal Cutting-1
3	P_StAC_aux_Metal Cutting-1(3)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(3)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(3)*t_idle Metal Cutting-1
4	P_StAC_aux_Metal Cutting-1(4)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(4)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(4)*t_idle Metal Cutting-1
5	P_StAC_aux_Metal Cutting-1(5)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(5)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(5)*t_idle Metal Cutting-1
6	P_StAC_aux_Metal Cutting-1(6)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(6)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(6)*t_idle Metal Cutting-1
7	P_StAC_aux_Metal Cutting-1(7)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(7)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(7)*t_idle Metal Cutting-1
8	P_StAC_aux_Metal Cutting-1(8)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(8)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(8)*t_idle Metal Cutting-1
9	P_StAC_aux_Metal Cutting-1(9)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(9)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(9)*t_idle Metal Cutting-1
10	P_StAC_aux_Metal Cutting-1(10)*t_cycleMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(10)*t_chMetal Cutting-1+P_StAC_aux_cons_Metal Cutting-1(10)*t_idle Metal Cutting-1

– E_tableservo_aux Metal Cutting-1=P_tableservo_aux_var_ Metal Cutting-1 (1)*rotary1backTime+P_tableservo_aux_cons_ Metal Cutting-1 (1)*t_cycle Metal Cutting-1+P_tableservo_aux_cons_ Metal Cutting-1 (1)*t_ch Metal Cutting-1+P_tableservo_aux_cons_ Metal Cutting-1 (1)*t_idle Metal Cutting-1

- E_StServo_aux Metal Cutting-1=P_StServo_aux_var_ Metal Cutting-1 (1)*st1processTime+P_StServo_aux_cons_ Metal Cutting-1 (1)*t_cycle Metal Cutting-1+P_StServo_aux_cons_ Metal Cutting-1 (1)*(t_ch Metal Cutting-1+t_idle Metal Cutting-1)
- E_ Metal Cutting-1_Filt_aux=P_ Metal Cutting-1_Filt_aux(1)*t_cycle Metal Cutting-1+P_ Metal Cutting-1_Filt_aux_cons(1)*t_ch Metal Cutting-1+ P_ Metal Cutting-1_Filt_aux_cons(1)*t_idle Metal Cutting-1
- E_ Metal Cutting-1_Chill_aux=P_ Metal Cutting-1_Chill_aux(1)*t_cycle Metal Cutting-1+P_ Metal Cutting-1_Chill_aux_cons(1)*t_ch Metal Cutting-1+ P_ Metal Cutting-1_Chill_aux_cons(1)*t_idle Metal Cutting-1
- E_tableAC_aux1 Metal Cutting-1=E_tableAC_aux Metal Cutting-1 (1)+P_tableAC_aux_cons_ Metal Cutting-1 (1)*t_ch Metal Cutting-1+P_tableAC_aux_cons_ Metal Cutting-1 (1)*t_idle Metal Cutting-1
- E_imorot_aux Metal Cutting-1=P_imorot_aux_ Metal Cutting-1 (1)*t_cycle Metal Cutting-1+P_imorot_aux_cons_ Metal Cutting-1 (1)*t_ch Metal Cutting-1+P_imorot_aux_cons_ Metal Cutting-1 (1)*t_idle Metal Cutting-1
- E_aux_tot First Parallel Machine in Grinding-1 =t_cycle_tot First Parallel Machine in Grinding-1 *(P_grinding_aux First Parallel Machine in Grinding-1 +P_kenfilt_aux First Parallel Machine in Grinding-1 +P_kfluidpump_aux First Parallel Machine in Grinding-1)+t_idle First Parallel Machine in Grinding-1 Grind*(P_grinding_aux_cons First Parallel Machine in Grinding-1 +P_kenfilt_aux_cons First Parallel Machine in Grinding-1)
- E_aux Metal Cutting-1=E_StAC_aux Metal Cutting-1 (1)+E_tableAC_aux1 Metal Cutting-1 (1)+E_imorot_aux Metal Cutting-1 (1)+E_tableservo_aux Metal Cutting-1 (1)+E_StServo_aux Metal Cutting-1 (1)+E_ Metal Cutting-1_Filt_aux(1)+E_ Metal Cutting-1_Chill_aux(1)

For auxiliary energy of Metal Cutting-1, all the related energies consumed are come together. This formula is repeated for each station (for all 10 stations) in Metal Cutting-1 machine such as in Table 3.10 below.

Table 3.10 Formulation for E_aux Metal Cutting-1 in "Expression" Module

	EXPRESSION VALUES
1	E_StAC_auxMetal Cutting-1(1)+E_tableAC_aux1Metal Cutting-1(1)+E_imorot_auxMetal Cutting-1(1)+E_tableservo_auxMetal Cutting-1(1)+E_StServo_auxMetal Cutting-1(1)+E_Metal Cutting-1_Filt_aux(1)+E_Metal Cutting-1_Chill_aux(1)
2	E_StAC_auxMetal Cutting-1(2)+E_tableAC_aux1Metal Cutting-1(2)+E_imorot_auxMetal Cutting-1(2)+E_tableservo_auxMetal Cutting-1(2)+E_StServo_auxMetal Cutting-1(2)+E_Metal Cutting-1_Filt_aux(2)+E_Metal Cutting-1_Chill_aux(2)
3	E_StAC_auxMetal Cutting-1(3)+E_tableAC_aux1Metal Cutting-1(3)+E_imorot_auxMetal Cutting-1(3)+E_tableservo_auxMetal Cutting-1(3)+E_StServo_auxMetal Cutting-1(3)+E_Metal Cutting-1_Filt_aux(3)+E_Metal Cutting-1_Chill_aux(3)
4	E_StAC_auxMetal Cutting-1(4)+E_tableAC_aux1Metal Cutting-1(4)+E_imorot_auxMetal Cutting-1(4)+E_tableservo_auxMetal Cutting-1(4)+E_StServo_auxMetal Cutting-1(4)+E_Metal Cutting-1_Filt_aux(4)+E_Metal Cutting-1_Chill_aux(4)
5	E_StAC_auxMetal Cutting-1(5)+E_tableAC_aux1Metal Cutting-1(5)+E_imorot_auxMetal Cutting-1(5)+E_tableservo_auxMetal Cutting-1(5)+E_StServo_auxMetal Cutting-1(5)+E_Metal Cutting-1_Filt_aux(5)+E_Metal Cutting-1_Chill_aux(5)
6	E_StAC_auxMetal Cutting-1(6)+E_tableAC_aux1Metal Cutting-1(6)+E_imorot_auxMetal Cutting-1(6)+E_tableservo_auxMetal Cutting-1(6)+E_StServo_auxMetal Cutting-1(6)+E_Metal Cutting-1_Filt_aux(6)+E_Metal Cutting-1_Chill_aux(6)
7	E_StAC_auxMetal Cutting-1(7)+E_tableAC_aux1Metal Cutting-1(7)+E_imorot_auxMetal Cutting-1(7)+E_tableservo_auxMetal Cutting-1(7)+E_StServo_auxMetal Cutting-1(7)+E_Metal Cutting-1_Filt_aux(7)+E_Metal Cutting-1_Chill_aux(7)
8	E_StAC_auxMetal Cutting-1(8)+E_tableAC_aux1Metal Cutting-1(8)+E_imorot_auxMetal Cutting-1(8)+E_tableservo_auxMetal Cutting-1(8)+E_StServo_auxMetal Cutting-1(8)+E_Metal Cutting-1_Filt_aux(8)+E_Metal Cutting-1_Chill_aux(8)
9	E_StAC_auxMetal Cutting-1(9)+E_tableAC_aux1Metal Cutting-1(9)+E_imorot_auxMetal Cutting-1(9)+E_tableservo_auxMetal Cutting-1(9)+E_StServo_auxMetal Cutting-1(9)+E_Metal Cutting-1_Filt_aux(9)+E_Metal Cutting-1_Chill_aux(9)
10	E_StAC_auxMetal Cutting-1(10)+E_tableAC_aux1Metal Cutting-1(10)+E_imorot_auxMetal Cutting-1(10)+E_tableservo_auxMetal Cutting-1(10)+E_StServo_auxMetal Cutting-1(10)+E_Metal Cutting-1_Filt_aux(10)+E_Metal Cutting-1_Chill_aux(10)

– E_aux Metal Cutting-1 total=E_aux Metal Cutting-1 (1)+ E_aux Metal Cutting-1 (2)+ E_aux Metal Cutting-1 (3)+ E_aux Metal Cutting-1 (4)+ E_aux Metal Cutting-1 (5)+ E_aux Metal Cutting-1 (6)+ E_aux Metal Cutting-1 (7)+ E_aux Metal Cutting-1 (8)+ E_aux Metal Cutting-1 (9)+ E_aux Metal Cutting-1 (10)

In this estimation, E_aux Metal Cutting-1 of each station is summed.

– E_aux Metal Cutting-2=E_StAC_aux Metal Cutting-2 (1)+E_tableservo_aux Metal Cutting-2 (1)+E_StServo_aux Metal Cutting-2 (1)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (1)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (1)

For the auxiliary energy of Metal Cutting-2, the energies come out of the Metal Cutting-2 are summed. This formula is repeated for each station (for all 15 stations) in Metal Cutting-2 machine.

Table 3.11 Formulation for E_aux Metal Cutting-2 in “Expression” Module

	EXPRESSION VALUES
1	E_StAC_aux Metal Cutting-2 (1)+E_tableservo_aux Metal Cutting-2 (1)+E_StServo_aux Metal Cutting-2 (1)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (1)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (1)
2	E_StAC_aux Metal Cutting-2 (2)+E_tableservo_aux Metal Cutting-2 (2)+E_StServo_aux Metal Cutting-2 (2)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (2)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (2)
3	E_StAC_aux Metal Cutting-2 (3)+E_tableservo_aux Metal Cutting-2 (3)+E_StServo_aux Metal Cutting-2 (3)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (3)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (3)
4	E_StAC_aux Metal Cutting-2 (4)+E_tableservo_aux Metal Cutting-2 (4)+E_StServo_aux Metal Cutting-2 (4)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (4)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (4)
5	E_StAC_aux Metal Cutting-2 (5)+E_tableservo_aux Metal Cutting-2 (5)+E_StServo_aux Metal Cutting-2 (5)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (5)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (5)
6	E_StAC_aux Metal Cutting-2 (6)+E_tableservo_aux Metal Cutting-2 (6)+E_StServo_aux Metal Cutting-2 (6)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (6)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (6)
7	E_StAC_aux Metal Cutting-2 (7)+E_tableservo_aux Metal Cutting-2 (7)+E_StServo_aux Metal Cutting-2 (7)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (7)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (7)
8	E_StAC_aux Metal Cutting-2 (8)+E_tableservo_aux Metal Cutting-2 (8)+E_StServo_aux Metal Cutting-2 (8)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (8)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (8)
9	E_StAC_aux Metal Cutting-2 (9)+E_tableservo_aux Metal Cutting-2 (9)+E_StServo_aux Metal Cutting-2 (9)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (9)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (9)
10	E_StAC_aux Metal Cutting-2 (10)+E_tableservo_aux Metal Cutting-2 (10)+E_StServo_aux Metal Cutting-2 (10)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (10)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (10)
11	E_StAC_aux Metal Cutting-2 (11)+E_tableservo_aux Metal Cutting-2 (11)+E_StServo_aux Metal Cutting-2 (11)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (11)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (11)
12	E_StAC_aux Metal Cutting-2 (12)+E_tableservo_aux Metal Cutting-2 (12)+E_StServo_aux Metal Cutting-2 (12)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (12)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (12)
13	E_StAC_aux Metal Cutting-2 (13)+E_tableservo_aux Metal Cutting-2 (13)+E_StServo_aux Metal Cutting-2 (13)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (13)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (13)
14	E_StAC_aux Metal Cutting-2 (14)+E_tableservo_aux Metal Cutting-2 (14)+E_StServo_aux Metal Cutting-2 (14)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (14)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (14)
15	E_StAC_aux Metal Cutting-2 (15)+E_tableservo_aux Metal Cutting-2 (15)+E_StServo_aux Metal Cutting-2 (15)+E_ Metal Cutting-1_Filt_aux Metal Cutting-2 (15)+E_ Metal Cutting-1_Chill_aux Metal Cutting-2 (15)

-E_aux Metal Cutting-2 total=E_aux Metal Cutting-2 (1)+ E_aux Metal Cutting-2 (2)+ E_aux Metal Cutting-2 (3)+ E_aux Metal Cutting-2 (4)+ E_aux Metal Cutting-2 (5)+ E_aux Metal Cutting-2 (6)+ E_aux Metal Cutting-2 (7)+ E_aux Metal Cutting-2 (8)+ E_aux Metal Cutting-2 (9)+ E_aux Metal Cutting-2 (10)+ E_aux Metal Cutting-2 (11)+ E_aux Metal Cutting-2 (12)+ E_aux Metal Cutting-2 (13)+ E_aux Metal Cutting-2 (14)+ E_aux Metal Cutting-2 (15)

In this estimation, E_aux Metal Cutting-2 of each station is summed.

- E_deburring=(1654.69/5)*12.5/220
- E_aux_total= E_aux Metal Cutting-1total+ E_aux Metal Cutting-2total+ (E_aux_tot First Parallel Machine in Grinding-1 * (First Parallel Machine in Grinding-1 processNumber/ (First Parallel Machine in Grinding-1 processNumber+ Second Parallel Machine in Grinding-1 processNumber)))+ (E_aux_tot Second Parallel Machine in Grinding-1 * Second Parallel Machine in Grinding-1 processNumber/ (First Parallel Machine in Grinding-1 processNumber+ Second Parallel Machine in Grinding-1 processNumber))+ E_aux_totGrinding-2+(E_aux_totFirstParallelMachineinGrinding-3*(totFirst Parallel Machine in Grinding-3 processNumber/(tot First Parallel Machine in Grinding-3 processNumber+ tot Second Parallel Machine in Grinding-3 processNumber)))+ tot Second Parallel Machine in Grinding-3*(tot First Parallel Machine in Grinding-3 processNumber/(tot First Parallel Machine in Grinding-3 processNumber+ tot Second Parallel Machine in Grinding-3 processNumber)))+E_deburring

<u>Cycle time formulations:</u>

Cycle time formulations written in simulation model are displayed as follows. Cycle time formulations for metal cutting operations are the same. Besides, for grinding operations, cycle time formulations are the same.

- t_cycle Metal Cutting-1= TMIN (Metal Cutting-1BetweenExits)
- t_cycle_totGrinding-2=(DAVG(grindingtotGrinding-2Mac.Number Scheduled)*shiftNumber* shiftLength*60*60/totGrinding-2processNumber)-t_idle totGrinding-2Grind

<u>Idle time formulations:</u>

Idle time formulations are listed as the following. Idle time formulations for metal cutting operations (Metal Cutting-1 and Metal Cutting-2) are the same. Idle time formulations for grinding operations (First Parallel Machine in Grinding-1, Second Parallel Machine in Grinding-1, totGrinding-2, First Parallel Machine in Grinding-3, and Second Parallel Machine in Grinding-3) are the same.

- t_idle Metal Cutting-1= (DAVG (Metal Cutting-1table.Number Scheduled) *shiftNumber*shiftLength*60*60-TMIN(Metal Cutting-1Between Exits) *what Metal Cutting-1)/what Metal Cutting-1
- t_idleGrinding-2Grind=FRQTIM(idleGrinding-2Mode, STATEVALUE (grinding idleGrinding-2Mac,Breakdown))/ idleGrinding-2processNumber
- t_idle First Parallel Machine in Grinding-1 = 1-DAVG(grinding First Parallel Machine in Grinding-1.Mac.NumberBusy)

<u>Tool change formulations:</u>

Tool change formulations are prepared for metal cutting operations. These formulations are the same for both Metal Cutting-1 and Metal Cutting-2. The formulation is written as follows:

- t_ch Metal Cutting-2= FAVG (Metal Cutting-2Mode, STATEVALUE (Metal Cutting-2table,ToolChange))* FCOUNT(Metal Cutting-2 Mode, STATEVALUE (Metal Cutting-2 table,ToolChange))/ what Metal Cutting-2

Process rate formulations:

Process rate formulations are prepared for only grinding operations except Grinding-2 because of not having parallel machines. The formulation is displayed as follows:

– First Parallel Machine in Grinding-1 processRate= First Parallel Machine in Grinding-1 processNumber/ (First Parallel Machine in Grinding-1 processNumber+ Second Parallel Machine in Grinding-1 processNumber)

Cost Formulations:

- Investment Cost:

After cost values and investment years of each machine in the line are assumed, then the investment cost formulation will be written as follows:

$$C_{investment}\ (summation\ formula) = \sum_{i=1}^{6} \frac{costofmachine\ i}{investment\ year\ of\ that\ machine\ i * the\ number\ of\ shifts\ in\ a\ year}, \text{i} = 1,\ldots,6$$

Then, the result of the summation formula above is multiplied by PartperShift in order to calculate the investment cost per crankshaft per shift in the production line as follows:

$$\text{C\_investment\_} = \left(\frac{summation\ \ formula\ \ above}{PartperS\ hift}\right)$$

It is known that the PartperShift is estimated after simulation run. Therefore, the cost optimisation will be made with the help of PartperShift changes.

- Energy Cost:

Energy Cost formulation is written as the following:

$$\text{C\_energy\_} = \left(\frac{C_{energy}}{936 * PartperS\ hift}\right)$$

The energy cost of the production line in a year is divided by PartperShift to get the cost per crankshaft. Moreover, the result will be also divided by the number of 936 which is the total number of shifts in a year to get the energy cost per crankshaft per shift in a line.

- Direct Labor Cost:

After the values of the parameters (labor salary, the number of labors working in the line, and the working hours of labors in the line) needed for estimation of direct labor cost are assumed, the formulation will be written as follows:

$$C_{directLabor} = \frac{Labor_{salary} * Labor_{number}}{24 * PartperShift}, \text{for Turkish Liras value}$$

24= 6*4, which means “6” refers the number of shifts that one labor works in a week, and “4” refers the number of weeks in a month to estimate the result per shift.

The direct labor cost estimated above shows the direct labor cost per crankshaft per shift according to Turkish Liras. The overall cost is going to be estimated according to Euro, therefore, this cost value will be turned into Euro value as follows:

$$C_{directLabor} = (C_{directLabor}\ fortl) * (tlToEuro), forEurovalue$$

- Total Material Cost:

In this estimation, the formula will be written as follows:

$$C_{totalMateria\ l} = \frac{C_{totalMaterial}}{(936 * PartperShift)}$$

- Overall Cost:

After calculation of each cost (amortisation, energy, direct labor, and total material) the summation of these costs will give the overall cost in the Type-A production line.

$$C_{overall} = C_{investment} + C_{energy} + C_{directLabor} + C_{totalMaterial}$$

"StateSet" Module:

The "*Stateset*" module defines states for a resource or number of resources in the model. The Resource module references the stateset, if any, that a given resource will use. The "StateSet" Module is displayed as Table 3.12.

Table 3.12 StateSet Module

NAME
Metal Cutting-1States
Metal Cutting-2States
First Parallel Machine in Grinding-1 States
Second Parallel Machine in Grinding-1 States
idleGrinding-2States
First Parallel Machine in Grinding-3States
Second Parallel Machine in Grinding-3States

"Set" Module:

The "Set" module defines various types of sets, consisting of resource, entity type e.t.c. Resource sets are used in the Process modules. Counter and Tally sets are used in the Record module. Queue sets can be used with the "Seize", "Hold", "Access", "Leave", "Request", and "Allocate" modules of the "Advanced Process" and "Advanced Transfer" panels. The written in "Set" Module is displayed in the Table 3.13.

Table 3.13 "Set" Module

NAME:
SetGonetoSand

Simulation Model Development:

The simulation model has been developed with using Arena 14 software. The screenshot view of the model is seen as follows as Figure 3.7:

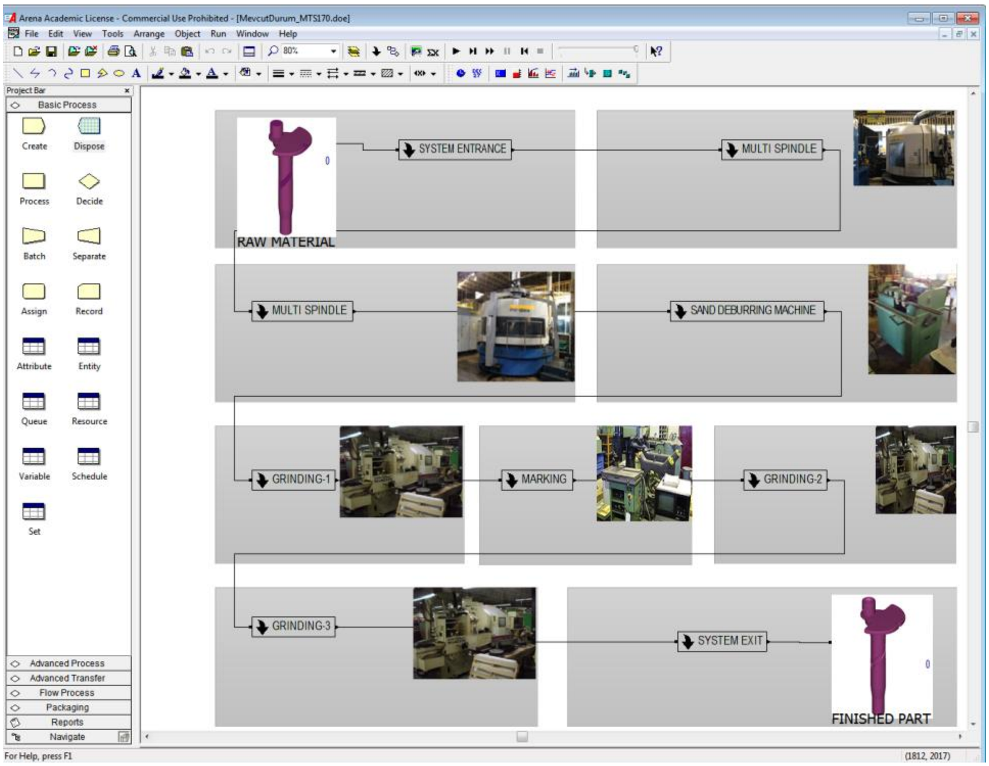

Figure 3.7 The screenshot of the model

The detailed screenshots of the above submodels are shown in Appendix A.

Verification and Validation of the Model

For the verification of the developed model, the behavior of the simulation model has been examined for different cases and flow types, and the similarity of the simulation model to the actual model has been observed.

Moreover, the rationality of the outputs taken from the model under different input sets and parameter values has been investigated.

In the validation process, both cycle time data and process time per shift data taken from the system have been compared with the outputs of the model. The Validation analysis has showed that the model closely represented the real system.

Design the Experiments

Alternative Scenarios:

Output Analysis:

In the existing system, all machines are open for 24 hours. The output analysis of the existing system shows that in the "Grinding-1 and Grinding-3" points, it is not needed for parallel grinding machines to be kept open for shift.

Several critical points where significant energy savings could be realized are identified in the Type-A crankshaft production line. During discussions with the line manager, it has been stated that all of the machines are operating in either processing or standby mode 24 hours a day, 7 days a week. On Sundays, Metal Cutting-1 has been operated for one additional shift to catch up with the manufacturing schedule while the others remaining in the idle state.

How Were the Alternative Scenarios Selected?

While alternative scenarios are being proposed to the existing system, it has been aimed to minimize the energy consumed by machine in standby position.

To do this, first of all, it has begun from the scenario that is estimated to give more benefit and then added the activities which give less benefit into this scenario, and moved on doing this process for each scenario. Scenarios are written accordingly as follows:

Scenario-0: “Sundays only Metal Cutting-1 works, all other machines are off.”
On Sundays, except Metal Cutting-1 machine, all the machines are kept in standby position in spite of not operating. This Scenario-0 has been proposed to minimize energy consumed by machines while they are open.

Scenario-1: “scenario-0+ Second Parallel Machine in Grinding-3 working only 4 hours in the morning and 4 hours in the afternoon.”
When the existing system model is run in Arena, it has been observed that on the one hand, at the Grinding-1, the utilization rate of First Parallel Machine in Grinding-1 is almost zero. On the other hand, at the Grinding-3, the utilization rate of Second Parallel Machine in Grinding-3 machine seems to be very small (around 60%). Managers have a reason about this result that keeping the machines on standby prevents increases in scrap rates since it takes time to reach the high tolerance process state, and the cost of stopping the line is higher than the standby energy cost.
After further investigations, it was found that approximately 10 minutes was a sufficient amount of time for the grinding machines to reach a steady state of operation. Based on this information, two additional alternative scenarios related to the grinding machines such as Scenario-1 and Scenario-2 are determined.In this Scenario, it is decided that Second Parallel Machine in Grinding-3 machine will operate 4 hours in the morning and 4 hours in the evening. Except these hours, the machine will be shut down.

Scenario-2: “scenario-1+ Second Parallel Machine in Grinding-1 is permanently off.”
In the Scenario-2, it will be aimed to eliminate the standby energy consumed by Second Parallel Machine in Grinding-1 machine while it is open with shutting down the machine completely considering the utilization rate of it.
When Second Parallel Machine in Grinding-1 in the “Grinding-1” point is closed and the Second Parallel Machine in Grinding-3 in the “Grinding-2” point is kept open per only determined hours, it has been observed that the amount of the finished product per shift will not be departed from the target point.

Scenario-3: “scenario-2+ batch sizes are doubled for models.”

After first three scenarios, it has been wanted to identify the effects of the increased throughput in the line. During the system analysis, engineers have stated that Metal Cutting-1 and Metal Cutting-2 machines require significant setup operations when crankshaft model is to be changed. Therefore, decreasing batch size will directly decrease the setup time.

Thanks to that, the time passed while the machines don’t machine any crankshaft, will decrease while operation time will increase, and the energy consumed by machines in the standby position will also decrease. It can be better for batch size to be determined with making optimization.

However, planning the frequency of model changes is a complicated process, which must consider many critical factors such as demand and supplier availability, production line availability, and stock levels. However, there couldn’t have enough data from the Firm.

When batch size is doubled experimentally, the profit that is made from this process is seen to be lower than that from the other scenario results. According to this experiment, there is enough information about the profit made from making the batch size be doubled.

In grinding process, the idle machine doesn’t operate and is held in standby position. When the idle machine is shut down and then switched on again, machine will need calibration. This is not feasible. Therefore, this is not taken as an alternative for the simulation study.

Design Alternatives:

<u>Output Analysis</u>:

Three different design alternatives and process plan improvements are investigated as well in this simulation study.

Aim of investigating different design alternatives is to evaluate and show how these alternatives for part design would change the embodied energy of the part, and to investigate and show the potential impacts on the process chain.

The design alternatives are listed as the Type-A (Existing System), casting, Type-B, and Spindle Stop&Optimization. Type-A is the base crankshaft design which has been modeled in the previous sections.

The first design alternative, casting, is a reduction in the amount of raw material used in Type-A casting. That means the impact of thinning all dimensions of casting by 1 mm. The second alternative, Type-B, is a completely different design that has a longer axial length compared to the Type-A. The last alternative, Spindle Stop&Optimization, is the optimization of the machining process parameters of Type-A, and results evaluation.

After deep investigation on the production line, it is seen that as the stations on rotating tables can only work in a synchronized way, bottleneck stations determine the cycle time of each machine. Reducing the cutting time (t_c) in bottleneck operations of Metal Cutting-1 and Metal Cutting-2 would improve the cycle time. As this would yield savings to E_{aux_total}, an optimization study is performed to decrease the cycle times of these operations. Features 3, 5, and 11 correspond to the operations at the bottleneck stations of 4 in Metal Cutting-1 and 3 in Metal Cutting-2, respectively.

It should be noted that in addition to the optimization studies which are proposing alternative scenarios and design alternatives to the Type-A crankshaft, multi-objective optimization will be made with using an optimization solver, OptQuest, as well.

Run the Experiments

Alternative Scenarios:

OutputAnalysis:

After the integration of alternative scenarios to the existing system, models have been run again. The total run length is 1 week for each simulation model. In the below Table 3.14, the amount of finished product per shift, the amount of auxiliary energy per part (E_part_aux (kJ)) for each alternative scenario, and the overall cost per crankshaft per shift will be seen. The outputs taken from the alternative scenarios simulation runs are displayed in Appendix C.

Table 3.14 The results of the Alternative Scenarios and Design Alternatives with respect to objectives in the system

		OBJECTIVES IN SIMULATION MODEL		
		OBJECTIVE-1	**OBJECTIVE-2**	**OBJECTIVE-3**
alternative scenarios	**description**	**Parts/shift**	**E_aux total (kJ)**	**C_overall (euro)**
Type-A (Existing System)	All stations on 24 hrs/7 days	1945,67	1098,83	5,91
Type-A (Scenario-0)	Sundays only Metal Cutting-1 works, all other machines are off	1955,78	980,13	5,88
Type-A (Scenario-1)	Scenario-0+ Second Parallel Machine in Grinding-3 working only 4 hrs in the mornings and 4 hrs in the afternoons	1955,78	915,97	5,88
Type-A (Scenario-2)	Scenario-1+ First Parallel Machine in Grinding-1 is permanently off	1955,78	884,72	5,88
Type-A (Scenario-3)	Scenario-2+ batch sizes are doubled for models	1989,83	874,76	5,77

Design Alternatives:

<u>Output Analysis:</u>

The design alternatives are modeled separately, run and their simulation results are reported. In the below Table 3.15, the amount of finished product per shift, the amount of auxiliary energy per part (E_part_aux (kJ)) for each design alternative, and the overall cost per crankshaft per shift will be seen. The outputs taken from the design alternatives simulation runs are displayed in Appendix C.

Table 3.15 The results of the What-if scenarios in the Design Alternatives with respect to objectives in the system

		OBJECTIVES IN SIMULATION MODEL		
		OBJECTIVE-1	**OBJECTIVE-2**	**OBJECTIVE -3**
design alternatives	**description**	**Parts/shift**	**E_aux total (kJ)**	**C_overall (euro)**
Type-A (Existing System)	All stations on 24 hrs/7 days	1945,67	1098,83	5,91
Casting	Reduction ofcasted raw material size	1976,22	1082,4	5,81
Type-B	Alternative design with various modifications	1875,33	1140,63	6,13
Optimization & Spindle Stop	Optimization of Type-A machining variables and full stop of idle spindles at Metal Cutting-1 Metal Cutting-2	1958,06	1080,82	5,87

Simulation will also yield the following outputs:

- energy consumption per each machine

The amount of energy consumption (kJ) per machine according to each alternative scenario and design alternative is listed as in the below Table 3.16.

It can be easily seen from the Table that the amount of energy consumption in the second parallel machine in Grinding-1 is recorded as infinity and shown with stars (e.g. ***) in the report of the simulation result in each alternative scenarios and design alternatives.

The reason is that in order to calculate the auxiliary energy consumed in this machine, the parameters used in the formulation are divided by the number of part machined in that machine. Even if that machine is run or shut down, because of the formula used for the estimation of the energy consumption, the result will always gives the infinity. However, this infinity does not reflect in the total auxiliary energy consumption due to its formula (total auxiliary energy consumption formula).

Table 3.16 Energy consumption per machine (kJ)

	Type-A (Existing System)	Type-A (Scenario-0)	Type-A (Scenario-1)	Type-A (Scenario-2)	Type-A (Scenario-3)	casting	Type-B	Optimization& Spindle Stop
Metal Cutting-1	310,69	290,59	290,59	290,59	288,36	305,84	320,26	306,04
Metal Cutting-2	344,62	308,31	308,31	308,31	305,32	339,56	361,18	333,56
Sand Deburring	18,8033	18,8033	18,8033	18,8033	18,8033	18,8033	18,8033	18,8033
First Parallel Machine in Grinding-1	36,6581	31,228	31,228	31,228	30,7441	36,0108	37,97	36,3989
Second Parallel Machine in Grinding-1	***	***	***	***	***	***	***	***
Grinding-2	120,18	102,38	102,38	102,38	100,76	118,19	124,48	119,34
First Parallel Machine in Grinding-3	107,25	91,7285	91,7285	91,7285	91,1483	106,38	108,55	107,26
Second Parallel Machine in Grinding-3	607,46	512,93	256,49	256,49	244,15	584,95	682,31	592,17

- Work in process (WIP) inventory

The amount of "WIP inventory" in the system is counted and listed as in the below Table 3.17.

Table 3.17 Work in process inventory in the system (amount)

	Type-A (Existing System)	Type-A (Scenario-0)	Type-A (Scenario-1)	Type-A (Scenario-2)	Type-A (Scenario-3)	casting	Type-B	Optimization& Spindle Stop
WIP	932	1100	1100	1100	1153	1021	1308	938

- Machine utilization

Machine utilization per machine is shown in the below Table 3.18. It is seen that utilization rate of the second parallel machine in Grinding-1 is zero. Therefore, this machine will be taken into consideration in the system.

Table 3.18 Machine utilization in the system

	Type-A (Existing System)	Type-A (Scenario-0)	Type-A (Scenario-1)	Type-A (Scenario-2)	Type-A (Scenario-3)	casting	Type-B	Optimization & Spindle Stop
Metal Cutting-1	0.54	0.59	0.59	0.59	0.59	0.53	0.55	0.54
Metal Cutting-2	0.60	0.73	0.73	0.73	0.74	0.64	0.76	0.62
First Parallel Machine in Grinding-1	0.52	0.58	0.58	0.58	0.59	0.53	0.50	0.53
Second Parallel Machine in Grinding-1	0	0	0	0	0	0	0	0
Marking	0.37	0.42	0.42	0.42	0.42	0.38	0.36	0.38
Grinding-2	0.59	0.65	0.65	0.65	0.66	0.60	0.57	0.59
First Parallel Machine in Grinding-3	0.44	0.49	0.49	0.49	0.49	0.45	0.44	0.44
Second Parallel Machine in Grinding-3	0.22	0.25	0.25	0.25	0.26	0.23	0.20	0.23

Analyze Results

Alternative Scenarios:

After the evaluation of alternative scenarios 0, 1, and 2, it is seen that the shut down of the machines when they are not used, makes the amount of energy per part decrease. Alternative scenario 3 has reduced the frequency of model and diameter change by half and in the time of extra setups production has been kept on, so that the amount of the finished goods has increased and the auxiliary energy consumption per part has also been reduced.

However, the reduction of the frequency of demand and diameter change is not a decision made by only the production department. It is important that this decision should be made by the sales and production departments paying attention to the demand frequencies and variations. When the demand frequently changes, and the changes are not predicted in advance, these make the needed amount of setups not adjusted. Every time, while departments are determining lot size to be produced, not only demand changes but also material holding and shortage costs are needed to be taken into consideration.

According to the Table 3.19, it is seen that handling and indirect energies are stable in each scenario. If all of the alternative scenarios are implemented consecutively, 10.4% energy savings can be realized and the part's value-added energy (VAE) will increase from 37.2% to 41.6%.

It is interesting to see that the most significant gains are associated with the first scenario, where all machines except Metal Cutting-1 are simply turned off on Sunday when they are not in use.

Value-added energy (VAE) can be calculated with the help of Theoretical energy of each machine, Auxiliary energy of each machine (these are process energies), Auxiliary energy of each machine taken from simulation run, process rates of each grinding machine, Indirect energy, and Transportation energy. The formula can be written as follows:

$$VAE$$

When the overall cost is considered, it will be seen from the results Table that the overall cost will change with respect to PartperShift. In Scenario-0, Scenario-1, and Scenario-2, PartperShift will remain the same so will the overall cost. These Scenarios have 0,5 % less overall cost/part than Existing System. In Scenario-3, the overall cost is 2,3% less than the Existing System.

Table 3.19. Alternative Scenarios and their estimated improvements

Alternative Scenarios	Description	Parts/Shift (#)	E_theoretical (kJ)	E_aux_process (kJ)	E_aux_idle (kJ)	E_handling (kJ)	E_indirect (kJ)	E_part (kJ)	VAE_part (%)	E_part saving (%)
As-is system	As-is system with all machines on 24/7	1945,67	82,4	719,3	379,8	21,7	949,9	2153,1	37,20%	NA
Sunday machine off	On Sundays, Metal Cutting-1 operates for one additional shift, all other machines are off	1955,78	82,4	719,6	260,6	21,7	949,9	2034,1	39,40%	5,50%
Grinding station-3	Scenario-0+ Second parallel machine in Grinding-3 operates only for 2 hours during the first half and 2 hours during the second half of each shift	1955,78	82,4	719,6	196,4	21,7	949,9	1970	40,70%	8,50%
Grinding station-1	Scenario-1+ First parallel machine in Grinding-1 is permanently off	1955,78	82,4	719,6	165,2	21,7	949,9	1938,7	41,40%	10,00%
Batch sizes double	Scenario-2+ batch sizes are doubled for models	1989,83	82,4	720,5	154,2	21,7	949,9	1928,7	41,60%	10,40%

On a machine basis, the effects can be validated by the below graphs in Figures 3.8 and 3.9. Turning off machines on Sunday (Scenario-0) reduces E_{aux_total} of all machines and increases the VAE of each machine.

Scenario-1, which is related with Grinding-3, reduces E_{aux_total} of Second Parallel Machine in Grinding-3 significantly and increases its VAE sharply. Moreover, in Scenario-2, turning off Second Parallel Machine in Grinding-1 cuts all idle energy of First Parallel Machine in Grinding-1. The last Scenario does not affect any single machine considerably but leads to a total energy reduction of 10 kJ throughout the chain.

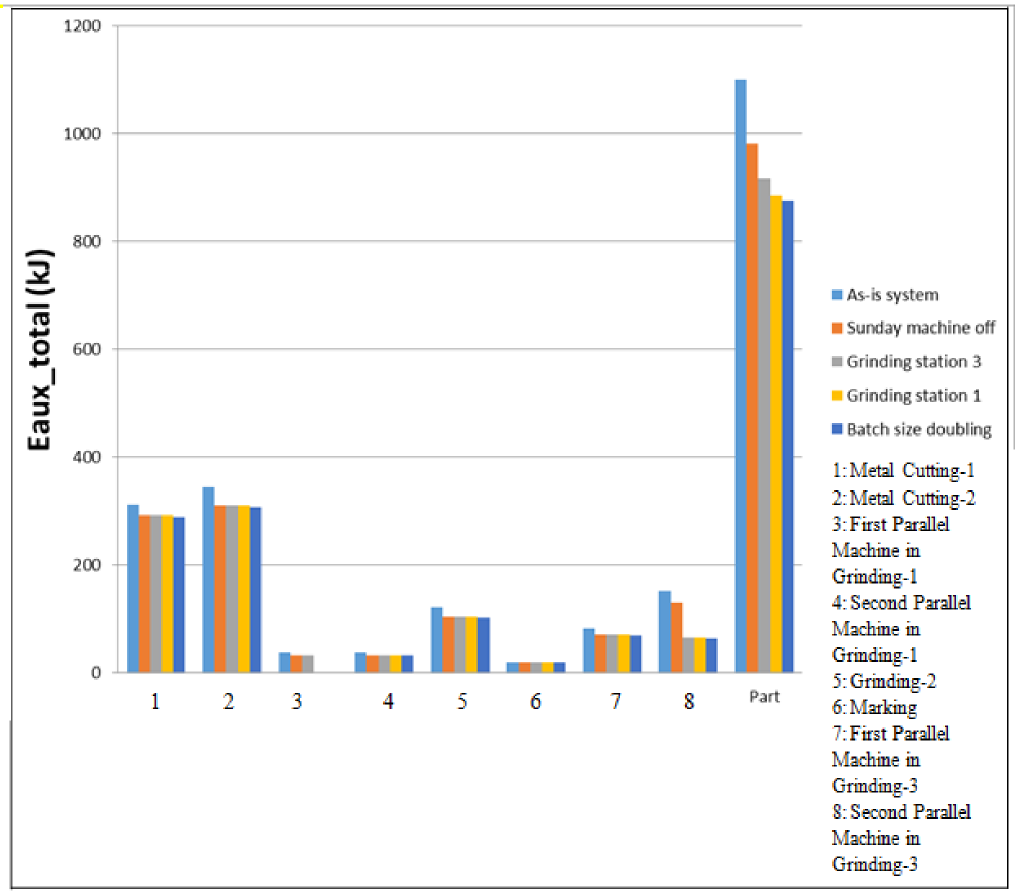

Figure 3.8. E_{aux_total} of alternative scenarios per machine

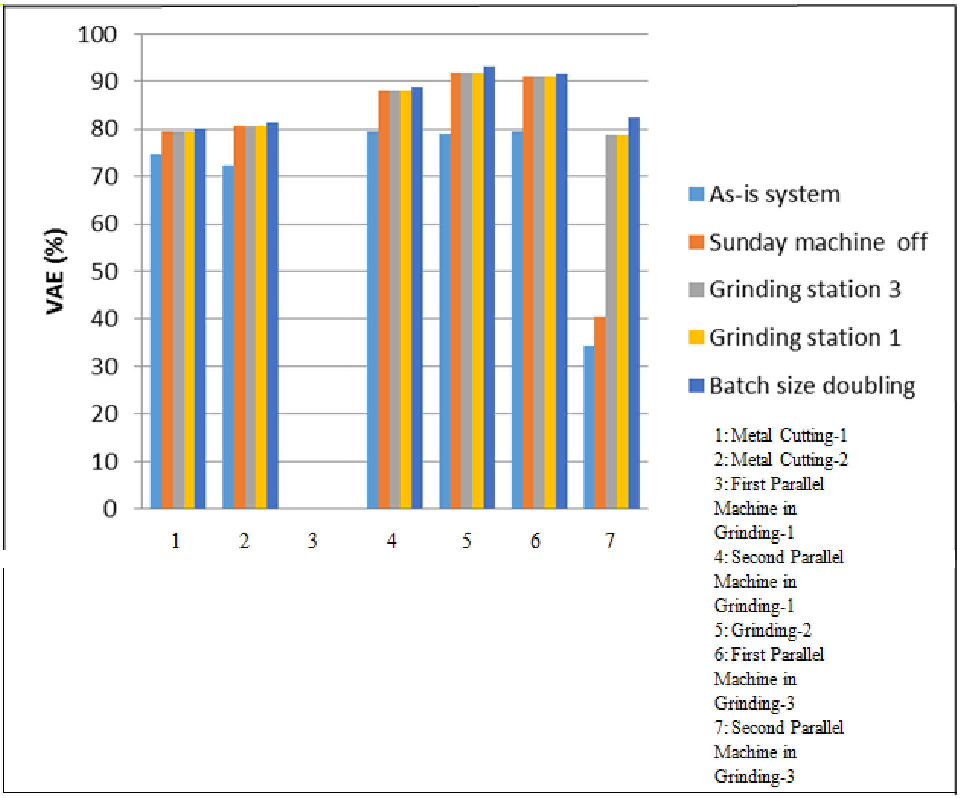

Figure 3.9. Value added energy of alternative scenarios per machine

Design Alternatives:

It is easily seen from the Table 3.15 that the design alternative, casting, uses 1.2% less energy whereas the design alternative, Type-B, consumes 2% more energy/part. The last design alternative, Spindle Stop & Optimization consumes 0.8% less energy/part.

Table 3.20 displays the results of each design alternative and its impact on each part manufactured regarding energy consumption. It is seen that handling and indirect energies are stable in each design alternative.

Table 3.20. Design alternatives and their estimated improvements

Design Alternatives	Description	Parts/Shift (#)	E_theoretical (kJ)	E-aux total (kJ)	E_handling (kJ)	E_indirect (kJ)	E_part (kJ)	VAE_part (%)	E_part saving (%)
Type-A	Baseline design	1946	82,4	1099,1	21,7	949,9	2153,1	37,20%	NA
casting	Reduction of casted raw material size	1976	74	1082,4	21,7	949,9	2128	37,00%	1,20%
Type-B	Alternative design with various modifications	1875	84,7	1140,6	21,7	949,9	2196,9	37,90%	-2,00%
Optimization & Spindle Stop	Optimization of Type-A machining variables and full stop of idle spindles at Metal Cutting machines	1958	82,4	1080,8	21,7	949,9	2134,8	36,90%	0,80%

Below Figures 3.10 and 3.11 reveal the aforementioned 4 alternatives' impacts on the manufacturing chain in terms of the energy breakdown of each machine and VAE of equipment.

Due to the reduction in raw material in casting, the impact on Theoretical energy can be seen clearly for the Metal Cutting-1 and Metal Cutting-2 machining stations. In Type-B, since it is slightly larger in volume, Theoretical energy also increases for Metal Cutting-1, Metal Cutting-2 and First Parallel Machine in Grinding-3. However, a sharp increase in Auxiliary idle energy can also be observed for the last station, Second Parallel Machine in Grinding-3, which can be attributed to increased process times at earlier stations. This can also be observed in Figure 3.11, as a VAE increases for Metal Cutting-1 and Metal Cutting-2, and decreases for Second Parallel Machine in Grinding-1, Grinding-2, Grinding-3 (both of the parallel machines).

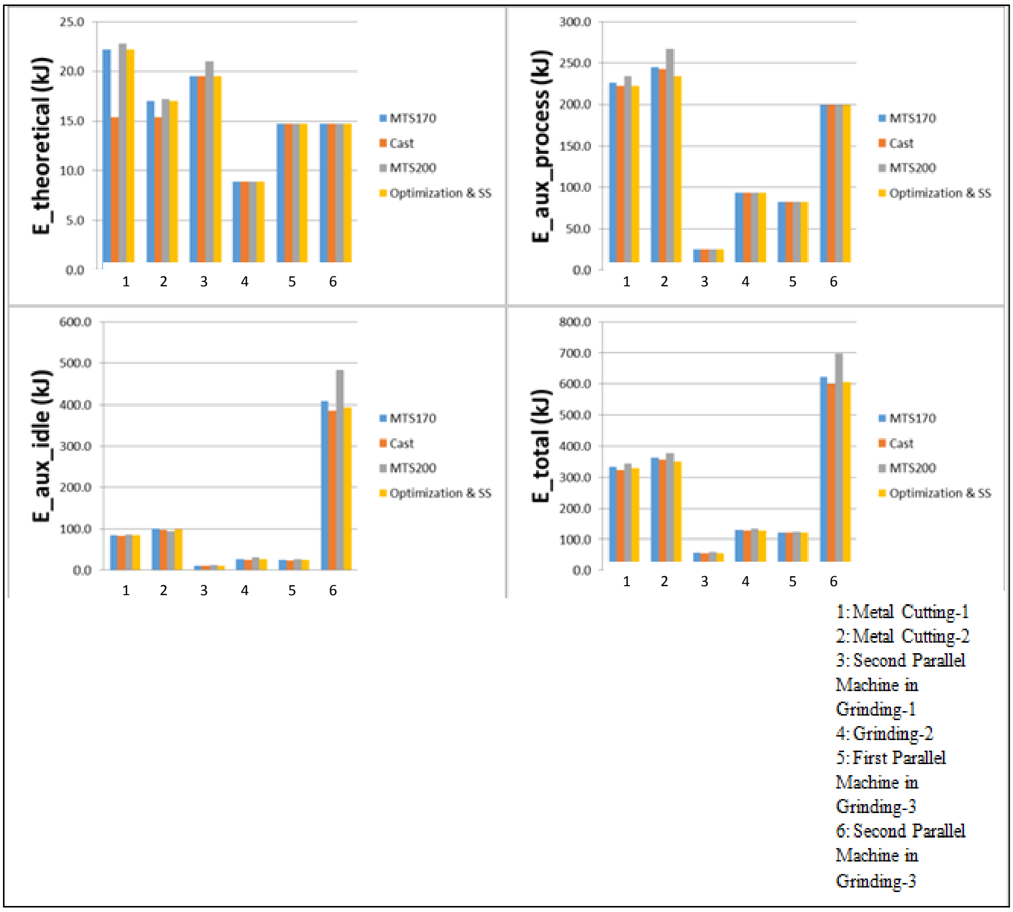

Figure 3.10. Energy consumption of Design Alternatives per machine

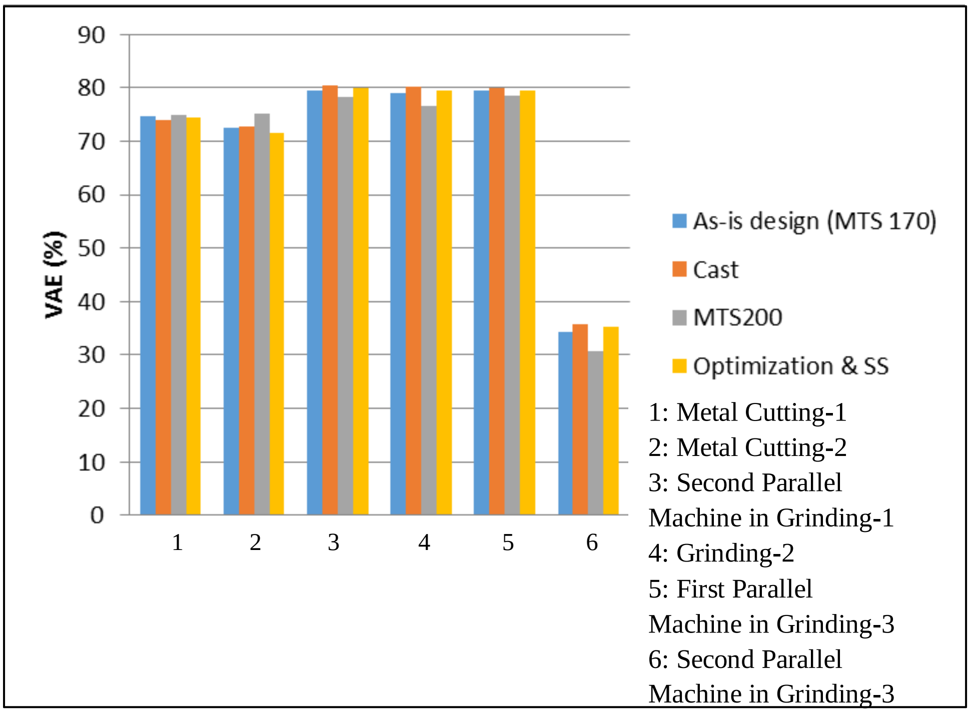

Figure 3.11. Value added energy of Design Alternatives per machine

When the overall cost is to be discussed, it can be easily seen that on the one hand, the design alternative, casting, will give the best overall cost per crankshaft per shift. On the other hand, the design alternative, Type-B will give the worst overall cost among all alternatives. That means it has 3,5% higher overall cost than the Existing System. Besides, all the design alternatives, except Type-B, will give the overall cost value which is lower than that in the existing system.

Get Insight

The application of the alternative Scenario-3 is dependent of the other departments and company strategy, so the Scenario-3 (the near-optimal solution) is adviced to be applied by the production department. Moreover, it is easily seen from the Table 3.14 above (the results of the alternative scenarios) that the Arena model is flexible to the other crankshafts being produced in the same production line.

Documentation

The simulation results with respect to objectives according to alternative scenarios and different crankshafts designs are given in the following Figures:

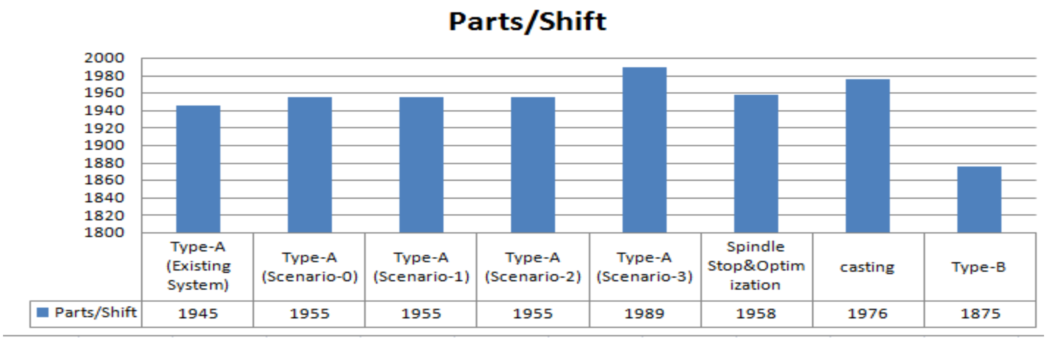

Figure 3.12. Maximization of the number of parts produced per shift

Figure 3.12 above represents the number of parts produced per shift in each alternative scenarios and design alternatives. There is an increasing trend in the results while increasing the scenario number in simulation.

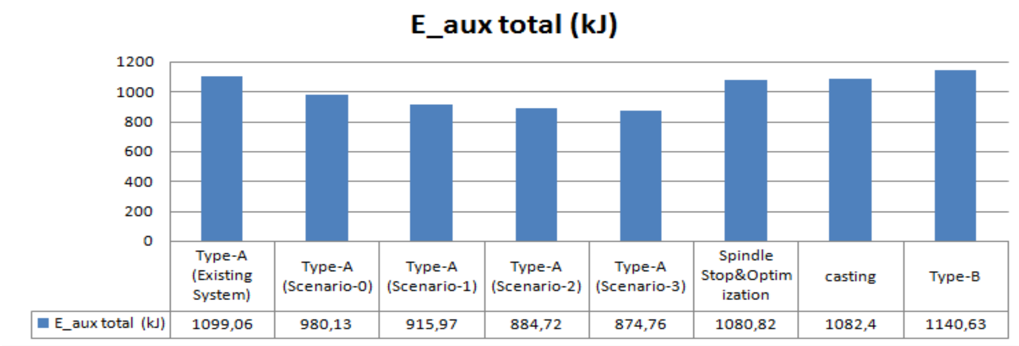

Figure 3.13 Minimization of the auxiliary energy consumption

In the graph drawn above Figure 3.13, a decreasing trend will be seen on the second objective called "the Minimization of the Auxiliary Energy Consumption in the Existing System". It means the higher the number of scenarios, the better the results of the objective is.

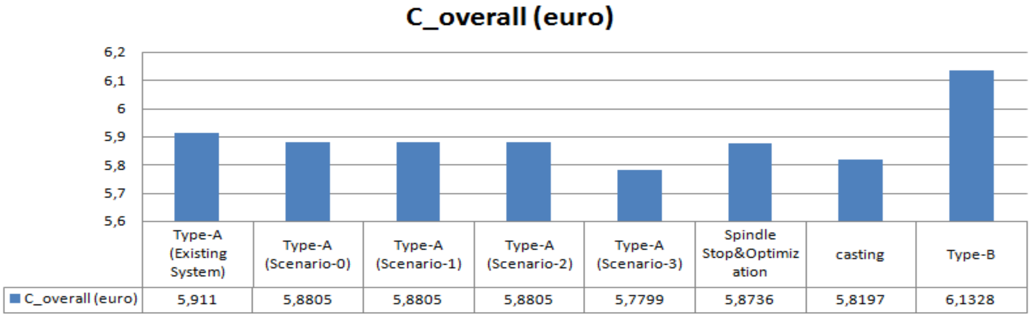

Figure 3.14. Minimization of the overall cost per crankshaft per shift

In the above Figure, the overall cost per crankshaft per shift can be seen with respect to existing system, each alternative scenario and design alternative. It can be observed that minimal changes occur on the overall cost of the models except that of Type-B.

The reason is that Type-B has a longer axial length which means the part will require higher process times to be machined. As a result, the number of parts produced per shift will decrease and this will lead to higher overall cost value in the system.

It is seen from the above three graphs that Scenario-3 seems to make more improvement on the existing system than the other Alternative Scenarios and the Design Alternatives.

3.3. Speed Up Of Type-A Crankshaft Production

In order to speed up the existing system model, four options exist as follows:

- Machines' Cutting times reduction (called Design Alternatives) in the production line,
- Speed up of conveyors in the production line,
- Robot times reduction in the production line,
- Propose Alternative Scenarios (the Scenarios mentioned before).

Machines' Cutting Times Reduction:

Cutting time changes are observed in Design Alternatives which are different designs from the original system. If it is asked whether the cutting times change affects the simulation result, especially on PartperShift and E_aux total adversely or not, the Design Alternatives which have been prepared before can be investigated in order to see the E_aux total changes.

When the Design Alternatives are considered according to "the speed up of production" principle, the results are listed as follows:

Table 3.21. Simulation Results of Existing System and Design Alternatives According to PartperShift and E_aux total

EXISTING SYSTEM	**OUTPUT**
PartperShift	1945.67
E_aux total	1098.83
casting	**OUTPUT**
PartperShift	1976
E_aux total	1082.4
Type-B	**OUTPUT**
PartperShift	1875
E_aux total	1140.6
OPTIMIZATION& SPINDLE STOP	**OUTPUT**
PartperShift	1958
E_aux total	1080.8

When these values are drawn in a Figure 3.15 as below, the Design Alternatives and Existing System will be easily compared with each other with respect to the PartperShift and E_aux total. It is known that the increment in the number of parts produced per shift will reflect the speed up of the production in the Facility.

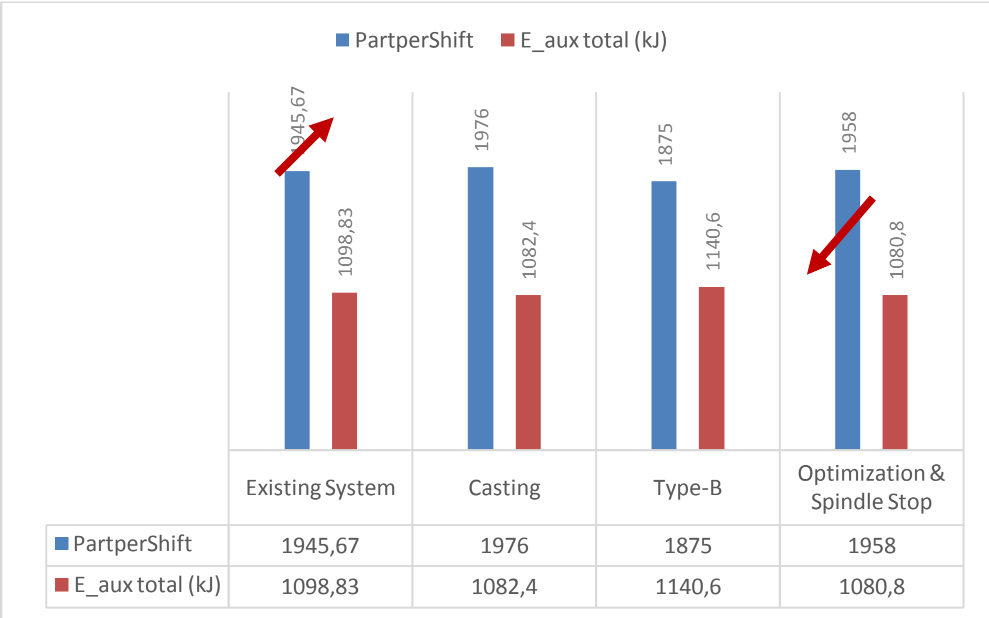

Figure 3.15. Comparison of the Design Alternatives Results and the Existing System

In the above Figure 3.15, the values with the arrows show the optimum objective values taken among the Design Alternatives. It is important to be pointed out that the PartperShift will increase while the E_aux total will decrease in these models mentioned above. In casting, PartperShift will increase and E_aux total will decrease. In Type-B, PartperShift will decrease while E_aux total will increase. It shows that the speed up of the production will remain the same, therefore, it is seen that Type-B is not suitable for the system requirements.

In Optimization & Spindle Stop, PartperShift will increase when E_aux total will decrease. When the speed up is drawn as a Figure 3.16 with respect to the increasing PartperShift values, the result will be seen as follows.

The fastest Design Alternative, casting, will not give the optimum auxiliary energy saving in the Type-A crankshaft production line. Therefore, in that point, a trade-off can be made, Alternative Scenarios can be proposed, or robot time changes in the line can be considered to make improvement on both of PartperShift and E_aux total.

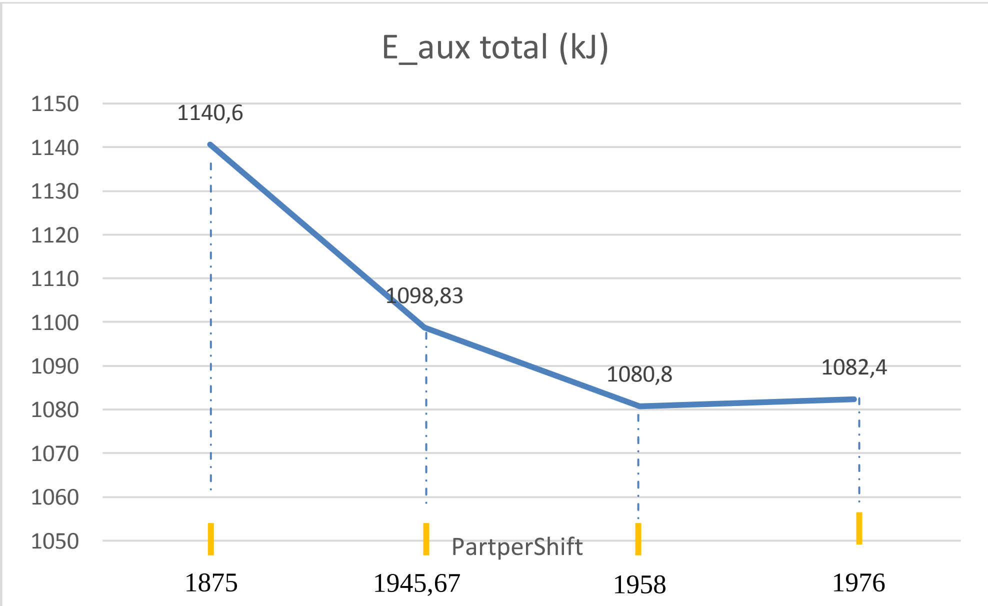

Figure 3.16. Changes in E_aux total With Respect to Increasing PartperShift Values in Existing System and Design Alternatives

Speed Up Of Conveyors:

Conveyors work as buffer areas on the production line. They have no positive or negative effects on the speed up of the system or anything else. Therefore, conveyors are neglected and not modeled in the simulation model.

Robot Times Reduction:

Robot times have effects on the speed up of the production as well. In order to observe their effects, robot times of each machine will be adjusted taking bottleneck stations into consideration. First of all, robot times of each machine will be adjusted.

Then, both of more than one machine robot time changes will be considered. Finally, the optimum robot time changes or both of more than one robot time changes that give the best result will be selected.

Options are listed as follows:

- Option 1: Only Metal Cutting-1 Robot Time Changes
- Option 2: Only Metal Cutting-2 Robot Time Changes
- Option 3: Both of Metal Cutting-1 and Metal Cutting-2 Robot Times Change
- Option 4: Only Grinding-1 Robot Time Changes
- Option 5: Both of Metal Cutting-1, Metal Cutting-2, and K140 Robot Times Change
- Option 6: Only Grinding-2 Robot Time Changes
- Option 7: Only Grinding-3 Robot Time Changes
- Option 8: Both of Metal Cutting-1, Metal Cutting-2, and Grinding-3 Robot Times Change

Table 3.22. Option Results Table

	PartperShift	E_aux total (kJ)
Existing System	1945,67	1098,83
Option 1: Only Metal Cutting-1 Robot times changes	1946,11	1098,66
Option 2: Only Metal Cutting-2 Robot Time Changes	1946,06	1062,1
Option 3: Both of Metal Cutting Machines' Robot Times Changes	**1946,39**	**1061,93**
Option 4: Only Second One of the Parallel Machines In Grinding-1 Robot Time Changes	1945,72	1098,83
Option 5: Both of Metal Cutting Machines and Second One of the Parallel Machines In Grinding-1 Robot Times Changes	1946,11	1061,97
Option 6: Only Grinding-2 Robot Time Changes	1945,67	1098,83
Option 7: Only Grinding-3 Robot Time Changes	1945,22	1098,88
Option 8: Both of Metal Cutting Machines and Grinding-3 Robot Times Changes	1945,72	1062,01

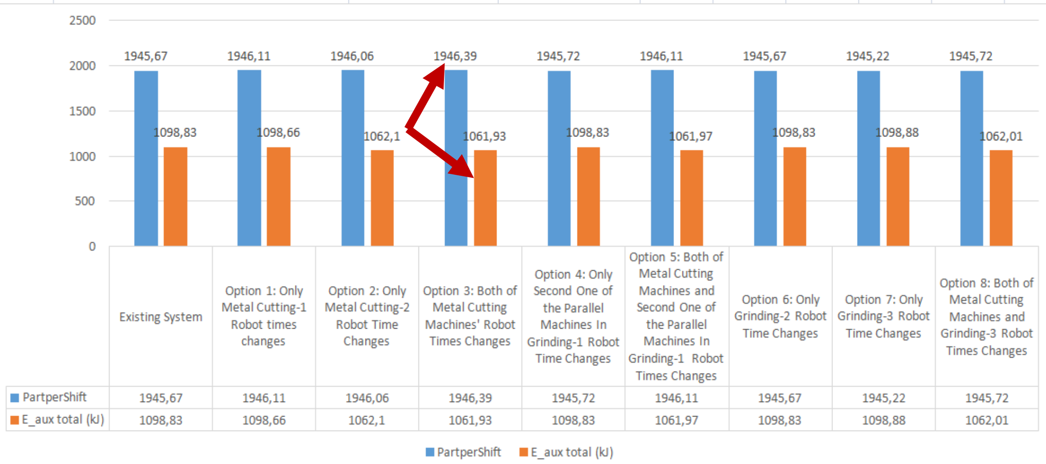

Figure 3.17. Machine Robots' Effect on Production Speed Up

Discussion:

In detail observation, Option results show that robot times' change in Grinding machines, First Parallel Machine in Grinding-1 and Second Parallel Machine in Grinding-1, will give similar results with the existing system simulation results, therefore, K140 machine robots will not be considered for speeding up the existing system model. The Grinding-2 grinding machine robot time' changes will give the same results with the original model results. Therefore, this grinding machine robot times are not necessary to be adjusted. Grinding-3 machines' robots have negative effects on the objectives considering speed up of production. As a result, Grinding-3 (both of the parallel machines) robots will be neglected in the "speed up of production".

It is seen from all of the Options that Option 3 which is "Both of Metal Cutting-1 and Metal Cutting-2 Robot Times Change" will give the optimum result among the other options. The results of the options can be easily seen from the Figure 3.17 above.

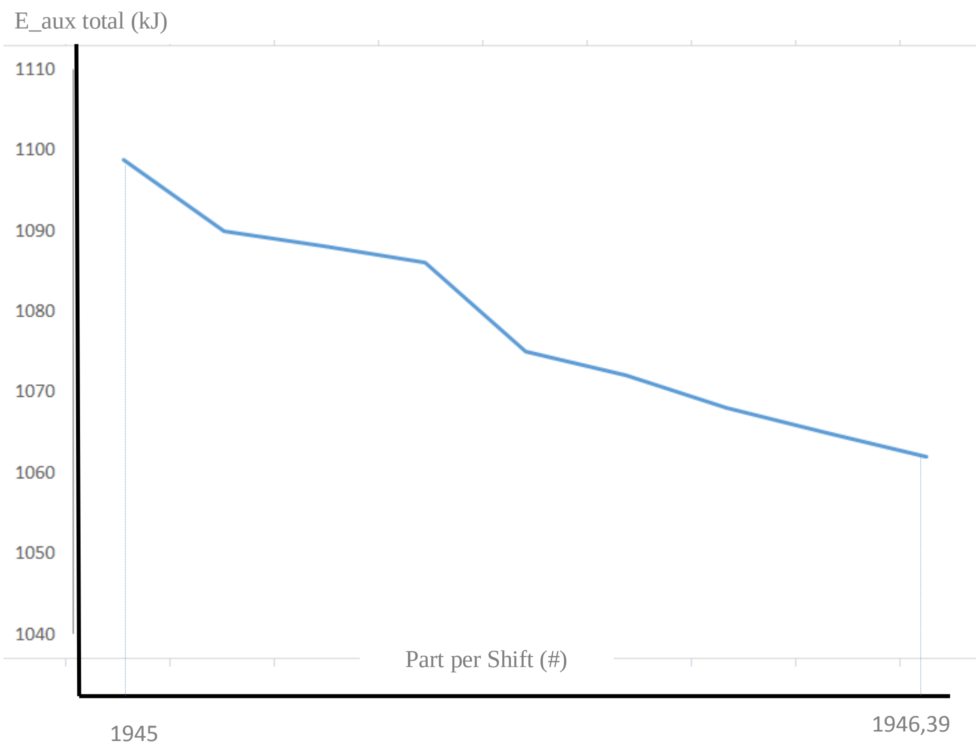

Figure 3.18. "Option 3" Production Speed Up Period

When the production speed up period is to be observed, the speed up can be easily drawn as the above Figure 3.18. Between 1945 and 1946.39 PartperShift values, the changes in E_aux total which may be considered as the auxiliary energy savings will have a decreasing trend.

Propose Alternative Scenarios:

Alternative Scenarios have been prepared to be aimed at minimizing the auxiliary energy consumed by machine in standby position before. If it is asked whether changing operation times of the determined machines and batch size doubling affect the simulation result, especially on PartperShift and E_aux total adversely or not. When the Alternative Scenarios are considered according to “the speed up of production” principle, the results are listed in the below Table 3.23 as follows:

Table 3.23. Simulation Results of Existing System and Alternative Scenarios According to PartperShift and E_aux total

Type-A (EXISTING SYSTEM)	**OUTPUT**
PartperShift	1945,67
E_aux total (kJ)	1098,83
Type-A (Scenario-0)	
PartperShift	1955,78
E_aux total (kJ)	980,13
Type-A (Scenario-1)	
PartperShift	1955,78
E_aux total (kJ)	915,97
Type-A (Scenario-2)	
PartperShift	1955,78
E_aux total (kJ)	884,72
Type-A (Scenario-3)	
PartperShift	1989,83
E_aux total (kJ)	874,76

In order to see the changes of objective values clearly, the results are drawn as follows:

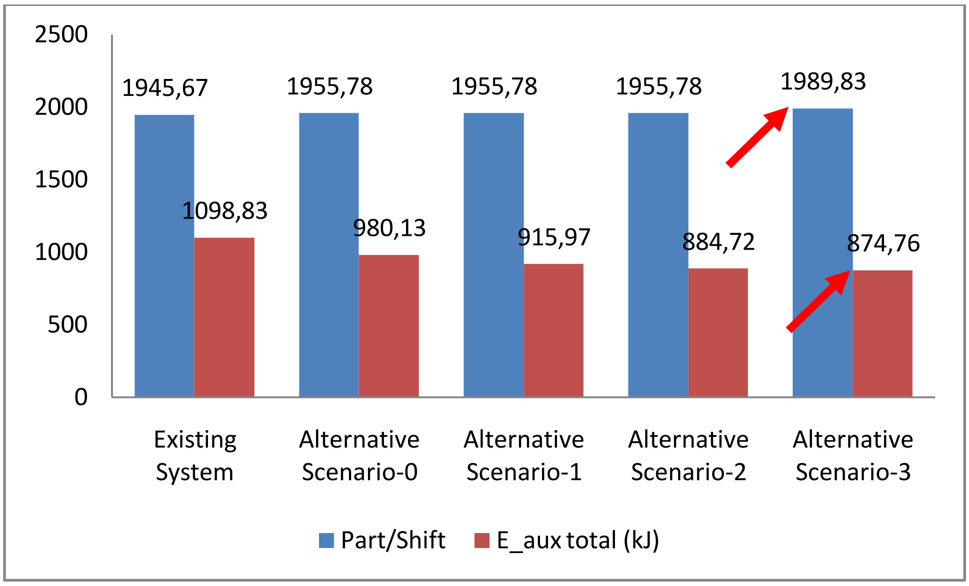

Figure 3.19. Comparison Between Existing System and Alternative Scenarios

In the above Figure 3.19, the values with arrows show the optimum results among the Alternative Scenarios results. When the speed up is drawn as a Figure 3.20 with respect to the increasing PartperShift values, the result will be seen as follows. It is seen that the last Scenario, Scenario-3, will lead to the optimum results with respect to PartperShift and E_aux total among the other alternatives results.

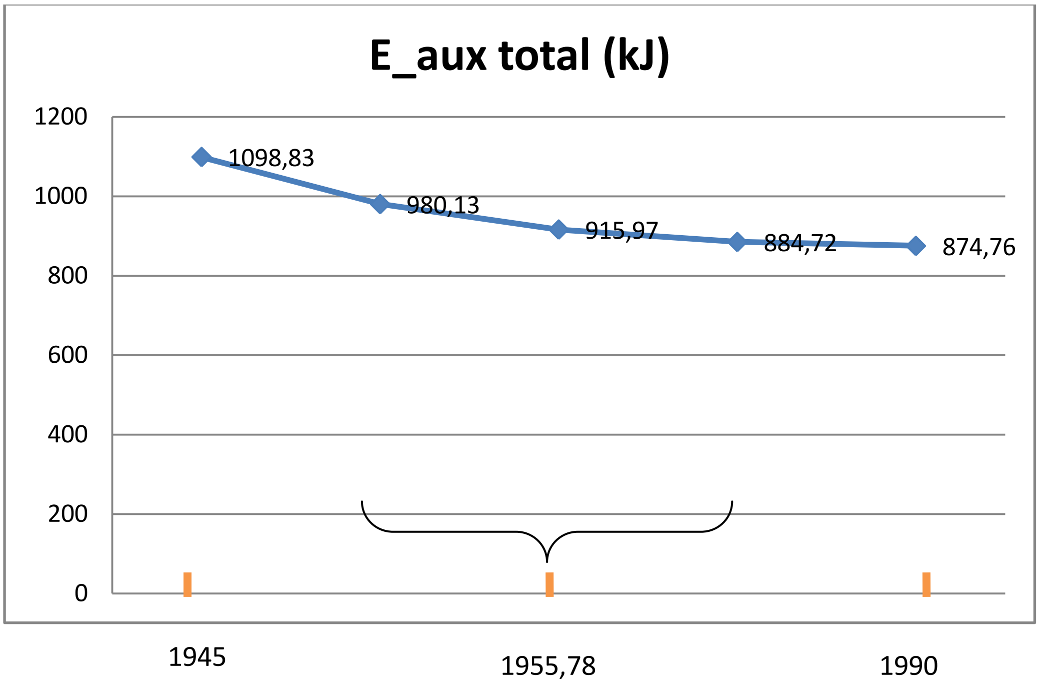

Figure 3.20. Changes in E_aux total with respect to Increasing PartperShift Values in Existing System and Alternative Scenarios

Comparison of Robot Time Changes (Best Option) with the Design Alternative Results:

In the previous papers, Design Alternatives and robot time changes have been investigated with respect to the Production Speed Up requirement. Each Design Alternative has been observed in terms of the values of PartperShift and E_aux total. Then, the optimum Design Alternative has been determined. After that robot times of each machine and the combination of the right machine robots' times considering bottleneck stations have been adjusted in order to speed up the Type-A crankshaft production.

The comparison of Design Alternatives and the optimum machine robot combination is written in the below Table 3.24 and drawn as the below Figure 3.21:

Table 3.24. Comparison of Robot Time Changes with the Design Alternative Results

	PartperShift	E_aux total (kJ)
Existing System	1945,67	1098,83
Design Alternative 1: casting	**1976**	1082,4
Design Alternative 2: Type-B	1875	1140,6
Design Alternative 3: Optimization & Spindle Stop	1958	1080,8
Both of Metal Cuttng Machines' Robot Times Changes	1946,39	**1061,93**

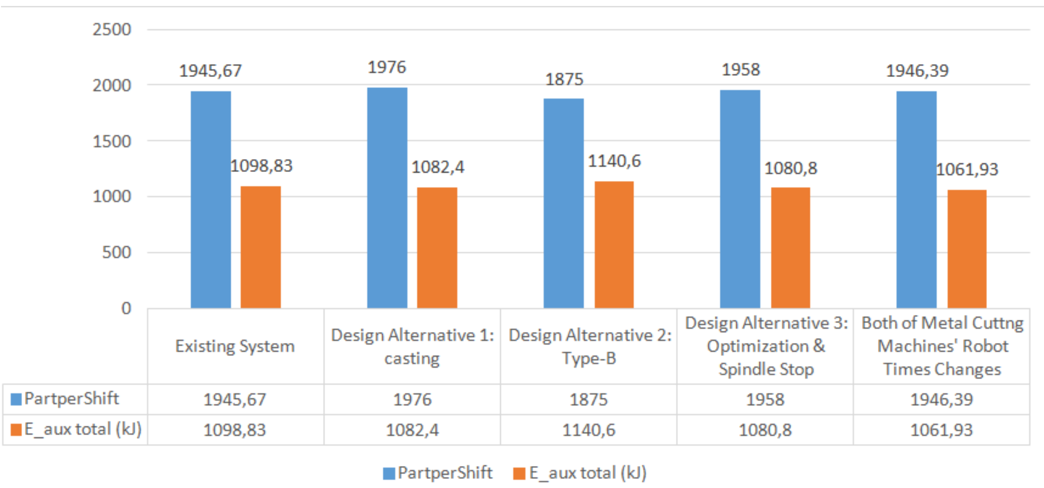

Figure 3.21. Comparison of Robot Time Changes with the Design Alternative Results

According to the results, it is seen that Design Alternative 1 will give the maximum PartperShift (1976 parts), however, it will not give the optimum E_aux total. When Metal Cutting-1 and Metal Cutting-2 robot times change together, both of PartperShift and E_aux total will be improved (1946 parts and 1061,93 kJ). PartperShift will increase a little bit but it will be necessary to see the speed up of the production.

When all of the options and alternatives are observed in detail, it can be logical to adjust the robot times of Metal Cutting-1 and Metal Cutting-2 together in order to speed up the production so far.

Comparison of Robot Time Changes (Best Option) with the Alternative Scenarios Results:

In the previous papers, Alternative Scenarios and robot time changes have been investigated with respect to the Production Speed Up requirement. Each Sceanrio has been observed in terms of PartperShift and E_aux total values. Then, the optimum scenario has been determined. After that robot times of each machine and the combination of the right machine robots' time considering bottleneck stations have been adjusted in order to speed up the Type-A crankshaft production.

The comparison of Alternative Scenarios and the optimum machine robot combination is written in the below Table 3.25 and drawn as the below Figure 3.22:

Table 3.25. Comparison of Robot Time Changes with the Alternative Scenario Results

	Part/Shift	**E_aux total (kJ)**
Existing System	1945,67	1098,83
Alternative Scenario-0	1955,78	980,13
Alternative Scenario-1	1955,78	915,97
Alternative Scenario-2	1955,78	884,72
Alternative Scenario-3	**1989,83**	**874,76**
Both of Metal Cutting-1 and Metal Cutting-2 Robot Times Change (Best Option)	1946,39	1061,93

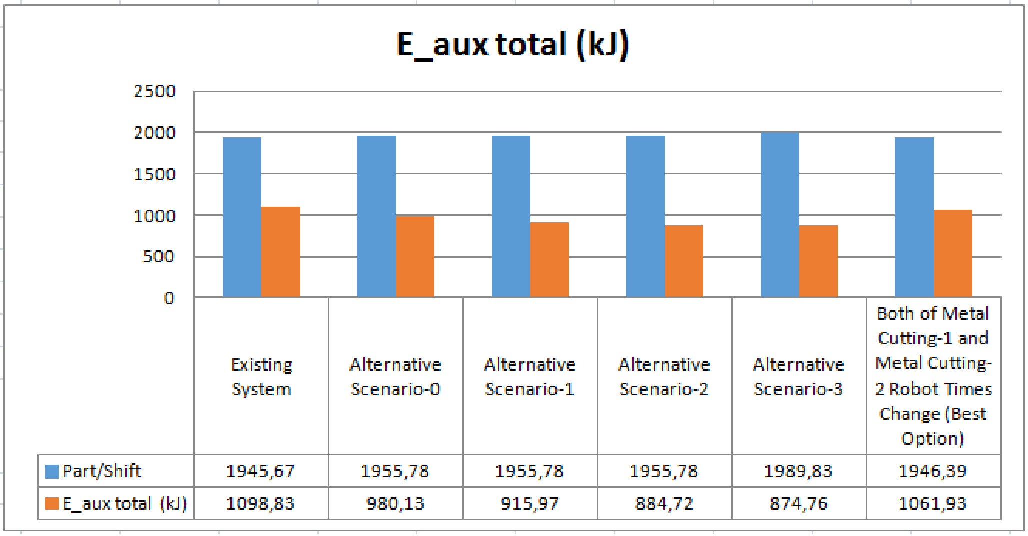

Figure 3.22. Comparison of Robot Time Changes with the Alternative Scenario Results

According to the results, it is seen that Scenario-3 will give the optimum results with respect to the objectives determined at the beginning of the study. It is clear that robot times' change have a direct effect on the objectives, however, the objective values taken by changing robot times are worse than that taken by proposing Alternative Scenario-3.

When all of the options and alternatives are observed in detail, it can be logical to apply modifications made in Alternative Scenario-3 in order to speed up the production and get optimum results.

In the next Chapter, Simulation-based Multi-objective Optimization will be investigated and made on the real system to get the near optimal solution for energy problem.

3.4. Simulation-Based Multi-Objective Optimization

3.4.1. Multi Objective Optimization

Multi-objective optimization problems are generally formulized as follows (Marler et al., 2004):

$$\underset{\mathbf{x}}{\text{Minimize}}\ \mathbf{F}(\mathbf{x}) = [F_1(\mathbf{x}), F_2(\mathbf{x}), \ldots, F_k(\mathbf{x})]^T$$

$$\text{subject to } g_j(\mathbf{x}) \leq 0, \quad j = 1, 2, \ldots, m,$$

$$h_l(\mathbf{x}) = 0, \quad l = 1, 2, \ldots, e,$$

In this formulation, "k" shows the number of objective functions, "m" and "e" refer the number of inequality and equality constraints respectively and "$F_i(x)$" are objectives in the system. When the maximization of any objectives is considered, these objectives are used with minus sign in the objective function. With the help of multi-objective optimization algorithm, more than one conflicting objectives are optimized (improved) at the same time in the short run.

3.4.2. Simulation Optimization

Simulation optimization links an optimization study with a simulation model for determining suitable settings of input parameters to optimize the system performance. This is clearly shown in the Figure 3.23 below.

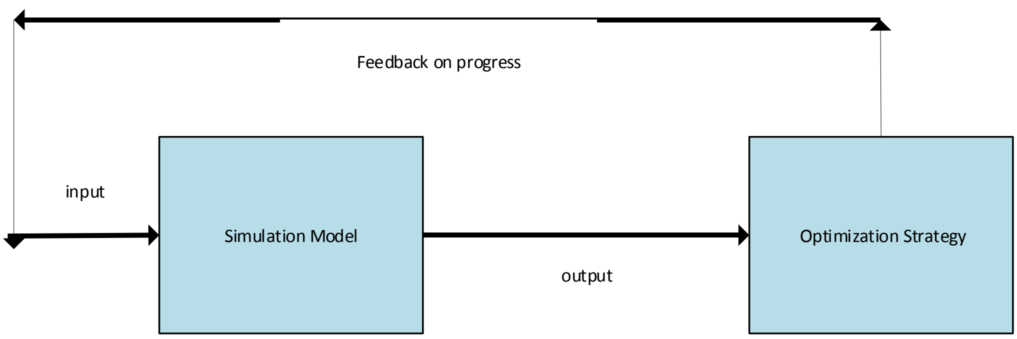

Figure 3.23 Simulation Optimization Model (Carson et al., 1997)

In order to optimize the simulation model, OptQuest optimization solver is used in Arena software. A simulation optimization strategy can be displayed as the above Figure 3.11.

The detailed information of OptQuest, fields that are filled for the solver like “Controls”, “Responses”, “Constraints”, and “Objectives”, and the Results and Discussion are discussed as the following sections.

Information about OptQuest

In today's competitive surrounding, people are faced with many difficult decisions, like building facilities, managing inventories, e.t.c. Modeling a decision problem in Arena software tells users what performance measures they can expect using a certain strategy. A strategy used can be defined as a certain set of values for the controls. The strategy is also called as scenario and solution. It is noted that "solution" refers to the controls (which are inputs to the Arena simulation), *not* to the resultings of the performance measures (like responses, or outputs from the Arena simulation).

If goal is to find the best strategy without using OptQuest, the control values will have to be entered for one strategy users are considering into the Arena model, then run the simulation, and analyze the results, after that, enter a new set of control values, run the simulation again, and so on.

Generally, it is not clear how to adjust the control variables from one simulation to the next one. This search is impractical, because lots of alternatives can occur for the problem exists in the manufacturing system. OptQuest provides Arena with improved features by automating the search for an optimal strategy so that the best strategy is found in the short run.

Relationship between Arena Model and OptQuest

When OptQuest is set up, it will test the Arena model and load information from the model, consisting of the defined control and response variables, into its own database. Then the user proceeds to define the optimization problem using OptQuest's interface.

When the optimization runs:

1. OptQuest feeds a potential solution of the problem into the Arena model by setting the control values.
2. First of all, Arena runs one replication in order to evaluate the result.
3. Optimization solver takes the resulting response values from simulation model.
4. If OptQuest is set for multiple replications per simulation:

- It will instruct Arena to run another replication with the same solution.
- It will take the response values.
- It will repeat this cycle until the specified number of replications has been run.
- It will average the values obtained for the responses from this set of replications. This set of replications represents one simulation.

5. Then OptQuest analyzes the outputs of the simulation and then uses its intelligent search procedures to generate a new potential solution, which it then sends to Arena.

OptQuest repeats this process by running more than one simulation. Its ultimate goal is to find the best solution that optimizes (maximizes or minimizes) the model’s objective value. Once optimization solver exits, the control variables in the Arena model are returned to their original values. The simulation model is unaffected by the solver.

Steps in OptQuest

Seven steps are included in the OptQuest Optimization process in the Arena. Steps are shown in the Figure 3.24 below:

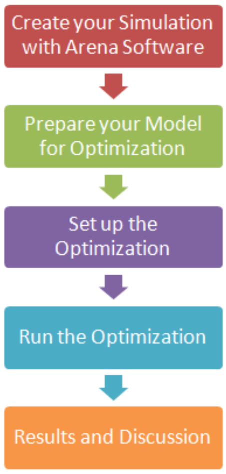

Figure 3.24 Steps in the Optimization Process In OptQuest Solver

<u>Create Simulation with Arena Software:</u>

Simulation model has been created at the beginning of this Chapter. Model has been run and the results are taken.

<u>Prepare Model for Optimization:</u>

Simulation model has been prepared for optimization. Then, optimization solver, OptQuest, is opened in the “Tool” toolbar in Arena software. Then, “New Optimization” button is clicked on to open the screen of the optimization solver.

<u>Set up the Optimization:</u>

There are four main parts that needs to be taken into account to set up and run the solver. These are “Controls”, “Responses”, “Objectives”, and “Constraints”. The detailed information is given as the following.

"*Controls*" are resources or variables in the model that users can manipulate. In this model, user-specified variables have been selected to be controlled. These are listed as follows:

– Robot times in each machine

After the controls are defined in this model, which controls to optimize in OptQuest can be selected. Optimization solver changes the values of these control variables with each simulation until OptQuest finds values yielding best objective.

In some of the analysis, the values of certain controls might be fixed and the rest might be optimized. The Controls node of the OptQuest tree displays the hierarchical structure of controls in Arena program. As the tree on the left are navigated, summary information will be displayed in a grid on the right.

If users want OptQuest to include a control in the optimization, it should be marked as "included". Controls can be included or excluded by clicking in the "included" column.To modify a control:

- Select the row including the control and click on the Modify button, or
- Select the node from the tree on the left, or
- Double-click on the row including the control.

The "*Responses"* node displays the hierarchical structure of responses in Arena software. When users navigate the OptQuest tree on the left, summary information is displayed in a grid on the right. Responses can also be used to prepare constraint and objective expressions. In order to make both a response to be included in the optimization problem and available for constraint and objective expressions, the "included" column is clicked in the Response summary grid.

It is important to know that "Responses" are output values of the simulation model. Therefore, they cannot be modified in OptQuest optimization solver. Responses in optimization solver are listed as follows:

- Auxiliary energies for all machines,
- Process numbers for all machines,
- Number back from deburring,
- Part per shift,
- Overall cost per crankshaft per shift,
- Cycle times for all machines,
- Idle times for all machines, and
- Process times for all machines.

The "*Objective*" function defines the goal of the optimization study. OptQuest for Arena allows users to define more than one objective, but only one objective can be used for an optimization at the same time. The other objectives created are ignored and have no impact on the optimization. If the "included" column for an objective is checked, that objective is included in the optimization problem.

In the optimization, multi objectives in the existing system will be optimized using Arena OptQuest Optimization Solver. The objectives are determined as the maximization of the number of parts produced, the minimization of the total auxiliary energy within the existing system and the overall cost per crankshaft per shift. The written objective in the "Objective" field is shown in the following Figure 3.25.

When *waste* (such as carbon emission) is considered as an objective, it is seen from the Literature Survey part that carbon emissions are related with the energy consumption. It means the less the amount of energy consumption is, the less the corresponding the amount of carbon emission is. Therefore, waste minimization is taken into account, but carbon emissions are neglected within the objective determination.

It is well known that multi-objective optimization problems includes more than one objectives that are conflicting (i.e. one objective can affect the other one adversely). However, in this system, there is no conflicting objective, so Pareto optimality is not taken into consideration.

NAME: OBJECTIVE
DESCRIPTION: the minimization of the total auxiliary energy consumption in the existing system
EXPRESSION: E_aux_total

- Minimize

Figure 3.25. Objective Named As "The minimization of the total auxiliary energy consumption in the existing system"

"*Constraints* define relationships among controls and/or responses in optimization problems. The "included" column for a constraint is checked when the constraint is to be included in the optimization. Only checked constraints are used while the optimization is being run. The rest are ignored. The constraints are defined as linear or nonlinear in the optimization. A linear constraint defines a linear relationship between controls and is a mathematical expression of linear terms added or subtracted. When the mathematical expression includes a response or a nonlinear term, constraint is defined as nonlinear. The constraints written in the optimization solver are shown as the following Figures 3.26- 3.27- 3.28.

Constraint-1 described as "the number of parts machined in Grinding-3 can be more than or equal to1800 parts" is related with the parallel machines operate in Grinding-3. The number of parts machined in both parallel machines in Grinding-3 reflects the number of parts produced per shift. In the existing system, the total number of finished crankshaft in each shift can be more than or equal to1800 parts. Therefore, the second objective related with the number of parts produced per shift can be shown as a constraint written like the Constraint-1.

Constraint-2 described as “the number of parts machined in First Parallel Machine in Grinding-1 is always greater than the one in Second Parallel Machine in Grinding-1” is related with the parallel machines that operate in Grinding-1. Constraint-2 shows that First Parallel Machine in Grinding-1 is the most effective machine among the parallel machines in Grinding-1 so that Second Parallel Machine in Grinding-1 cannot machine more parts than that in First Parallel Machine in Grinding-1.

Constraint-3 described as “the number of parts machined in Metal Cutting-1 is greater than or equal to the number of parts produced per shift”. That means Metal Cutting-1 is the first machine in the production line. In machining process of each machine, some of the parts are turned out to be the defective parts. Therefore, the number of parts enter the system to be machined at the beginning of the line are always greater than the number of finished parts in that shift.

NAME: Constraint-1
DESCRIPTION:the number of parts machined in Grinding-3 can be more than or equal to 1800 parts
EXPRESSION:1800<= [First Parallel Machine in Grinding-3 processNumber_]+[Second Parallel Machine in Grinding-3 processNumber_]

Figure 3.26. Constraint-1

NAME: Constraint-2
DESCRIPTION:the number of parts machined in First Parallel Machine in Grinding-1 is always greater than the one in Second Parallel Machine in Grinding-1
EXPRESSION:[Second Parallel Machine in Grinding-1 processNumber_]<=[First Parallel Machine in Grinding-1 processNumber_]

Figure 3.27. Constraint-2

NAME: Constraint-3
DESCRIPTION:the number of parts machined in Metal Cutting-1 is greater than or equal to the number of parts produced per shift
EXPRESSION:[PartperShift]<=[Metal Cutting-1processNumber_]

Figure 3.28. Constraint-3

Run the Optimization:

In the optimization solver, the parameter, which is robot time, is taken under control in order to optimize the total auxiliary energy consumption per crankshaft and the overall cost per crankshaft per shift.

In this section, Existing System, the Design Alternatives, casting and Optimization & Spindle Stop (these have optimum objective values among all the Design Alternatives), and the Alternative Scenario-3 (this will give the best objective values among all the Alternative Scenarios) models are going to be used for optimization.

While the optimization solver is being run controlling robot times of each machine, simulation is being run 100 times for optimization and the results are taken. The Existing system optimization result and the best solution taken from the optimization run are displayed as the following Figure 3.29.

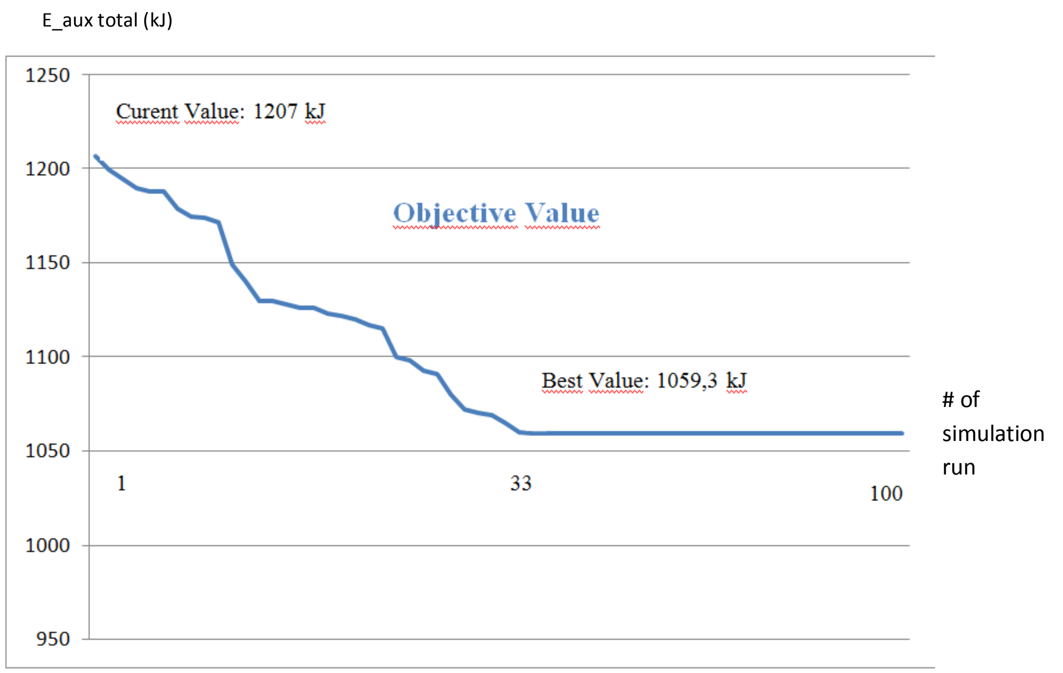

Figure 3.29. Existing System OptQuest Result

In the Figure 3.29 above, the current and best values of the objective, E_aux total, are shown. The blue line drawn shows the objective value taken from each simulation run (total run is 100). The number, 1, 33, and 100 indicates the number of simulation run for optimization.

Results and Discussion:

It is seen from the Figure that the objective value (which is related with E_aux total) starts with 1207 kJ and after 33 runs, it will get the optimum result, 1059,3 kJ. Then the optimization will continue with this value until the optimization will terminate in the 100th simulation run. When the other models have studied on for optimization with controlling robot times, the results can be seen as the following:

Table 3.26. Before-After Optimization Results of Simulation Models

	BEFORE OPTIMIZATION			AFTER OPTIMIZATION		
MODELS	Part Per Shift	E_aux total (kJ)	C_overall (euro)	Part Per Shift	E_aux total (kJ)	C_overall (euro)
Existing System	1945,67	1098,83	5,911	1946,39	1061,93	5,9089
Alternative Scenarios						
Scenario-3	**1989,83**	**874,76**	**5,7799**	**1991**	**874,24**	**5,7765**
Design Alternatives						
casting	1976,22	1082,4	5,8197	1976	1082,04	5,8203
Optimization&Spindle Stop	1958.06	1080.82	5.8736	1958	1080.49	5.8738

In the above Table 3.26, the objective values before optimization and after optimization can be easily seen. The determined models can be easily compared with each other in terms of the determined objectives. The difference of objectives' values between "before optimization" and "after optimization" is clearly seen in this Table. The red- colored values show the best values on those objectives.

According to the results, Alternative Scenario-3 gives optimum objective values in both of “before and after optimization” part. In this Scenario, after optimization, PartperShift have increased from 1945 parts to 1991 parts. E_aux total will decrease from 1098 kJ to 874 kJ. This will show 20,5% energy saving in the Existing System. Moreover, the overall cost will decrease from 5, 91 euro to 5, 77 euro. This shows 2,36% cost saving in Alternative Scenario-3.

In conclusion, it can be said that Alternative Scenario-3 leads to optimum objective values so that it will be adviced for the Firm to apply in their production line.

CHAPTER 4

CONCLUSIONS AND FUTURE WORKS

This research in manufacturing is mainly focused on the implementation of simulation-based multi-objective optimization. It focuses on realizing the modeling and simulation of a manufacturing environment using the software called Arena 14.0. In addition, the optimization program embedded in Arena software is demonstrated. The existing system model developed in Arena is examined according to Alternative Scenarios and Design Alternatives. Moreover, it is used as an input for optimization solver called OptQuest.

The expectation from a simulation study is supplying a scientific principle for making decisions about the existing system which is prepared in the software. The developed software provides the infrastructure in order to track the operation made in the production easily and it is the management's task to analyze the results of the simulation run and respond to the events of the system in the short run. As the final part of the study, optimization is made using the simulation model and presented.

Simulation models have been used for better estimation of the energy consumption within plants (Heilala et al., 2008; Herrmann and Thiede, 2009; Rahimifard et al., 2010). Simulation enables a more adaptive energy management strategy that not only predicts the future energy consumption using real time feedback, but also can optimize the energy distribution and conversions within the plant accordingly.The preparation procedures of the simulation and optimization studies and their outputs taken from ARENA helps users effectively use it in sustainable manufacturing environment.

The scope of the Thesis consists of modeling and optimization. It provides indications on the determination of modeling process parameters for sustainable manufacturing system and integration of the model with optimization solver.

In Type-A crankshaft production line, NTU crankshaft is also produced in the same line. For future study, the simulation model prepared can be modified considering NTU crankshaft. When it is done, the number of both Type-A and Type-C crankshafts produced can be easily monitored. Their energy consumptions per shift can be traced and reported.

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APPENDIX A

SUB MODELS IN THE EXISTING SYSTEM

The Sub Models in the system have been explained in detail in Chapter 3. This appendix shows only the screenshots of the Sub models prepared in ARENA® Software.

A.1 System Entrance Sub Model

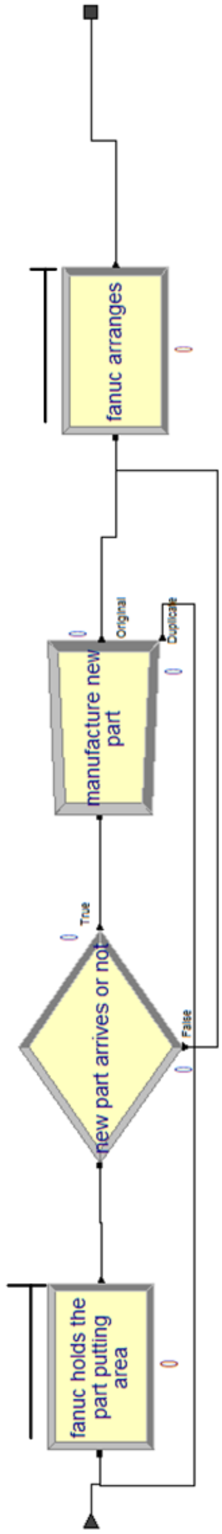


Figure A.1 System Entrance Sub Model

A.2 Multi-Spindle (Metal Cutting-1) Sub Model

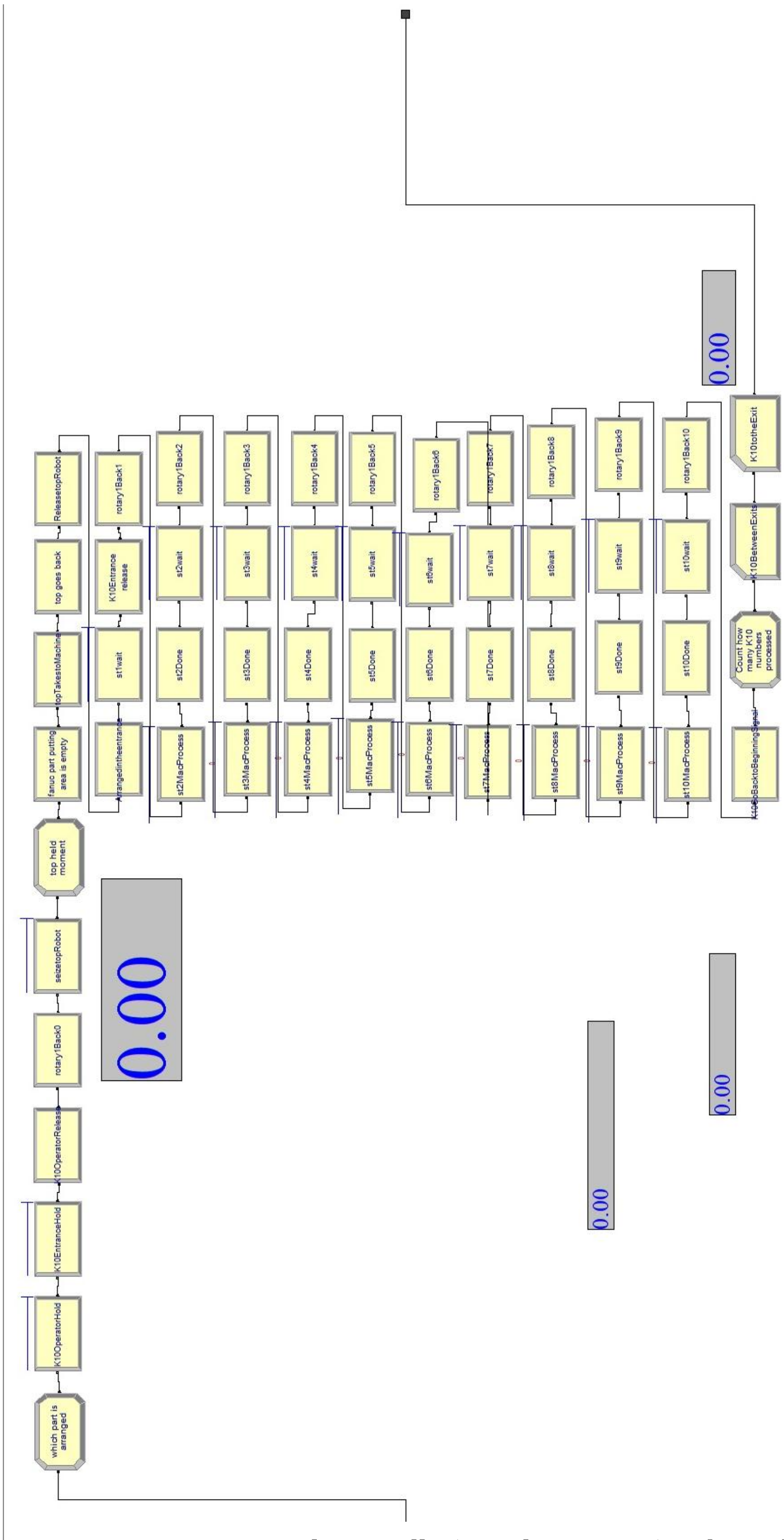


Figure A.2 Multi-Spindle (Metal Cutting-1) Sub Model

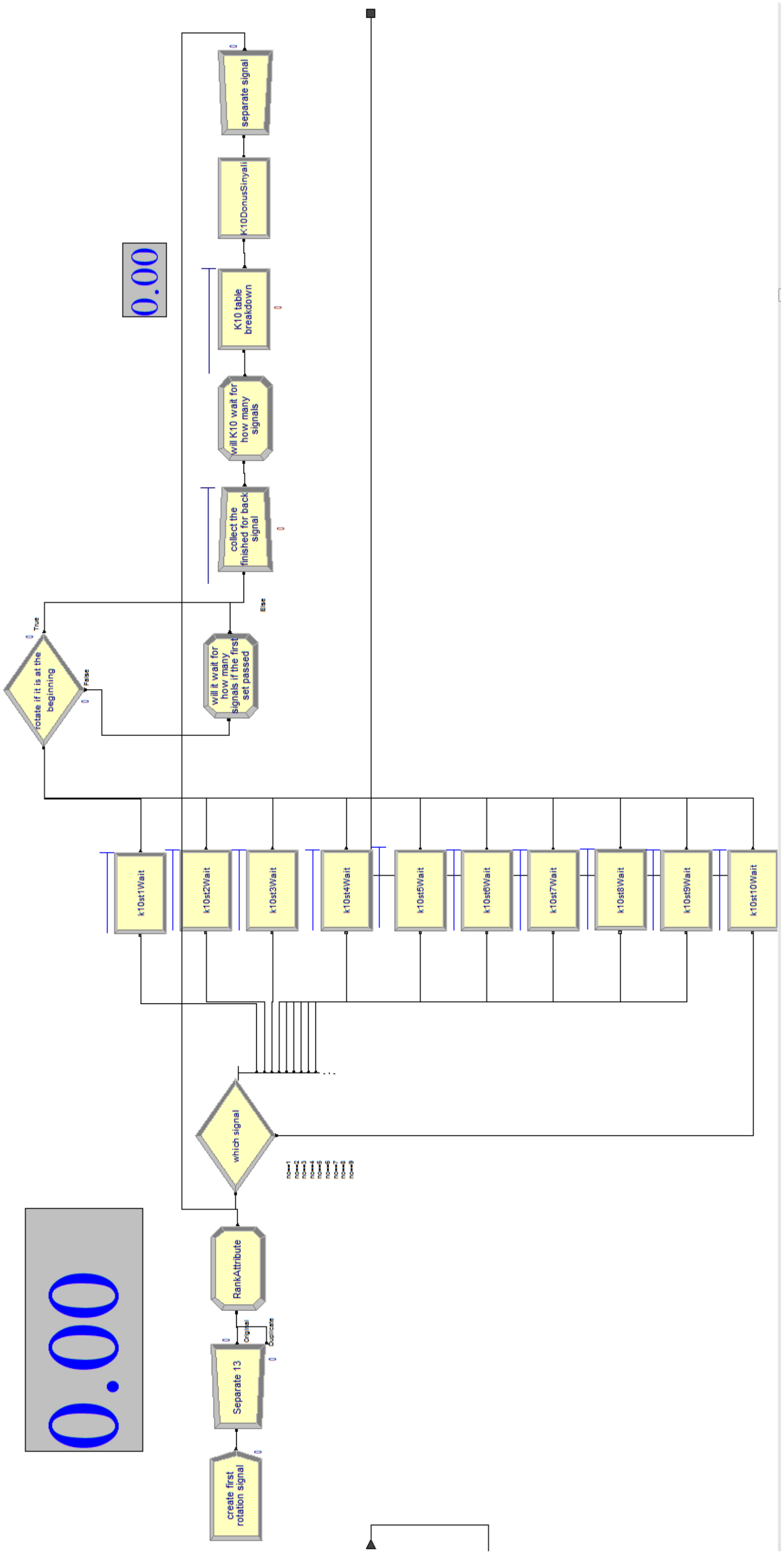


Figure A.3 Rotary Table Mechanism in Multi-Spindle
(Metal Cutting-1) Sub Model

A.3 Multi-Spindle (Metal Cutting-2) Sub Model

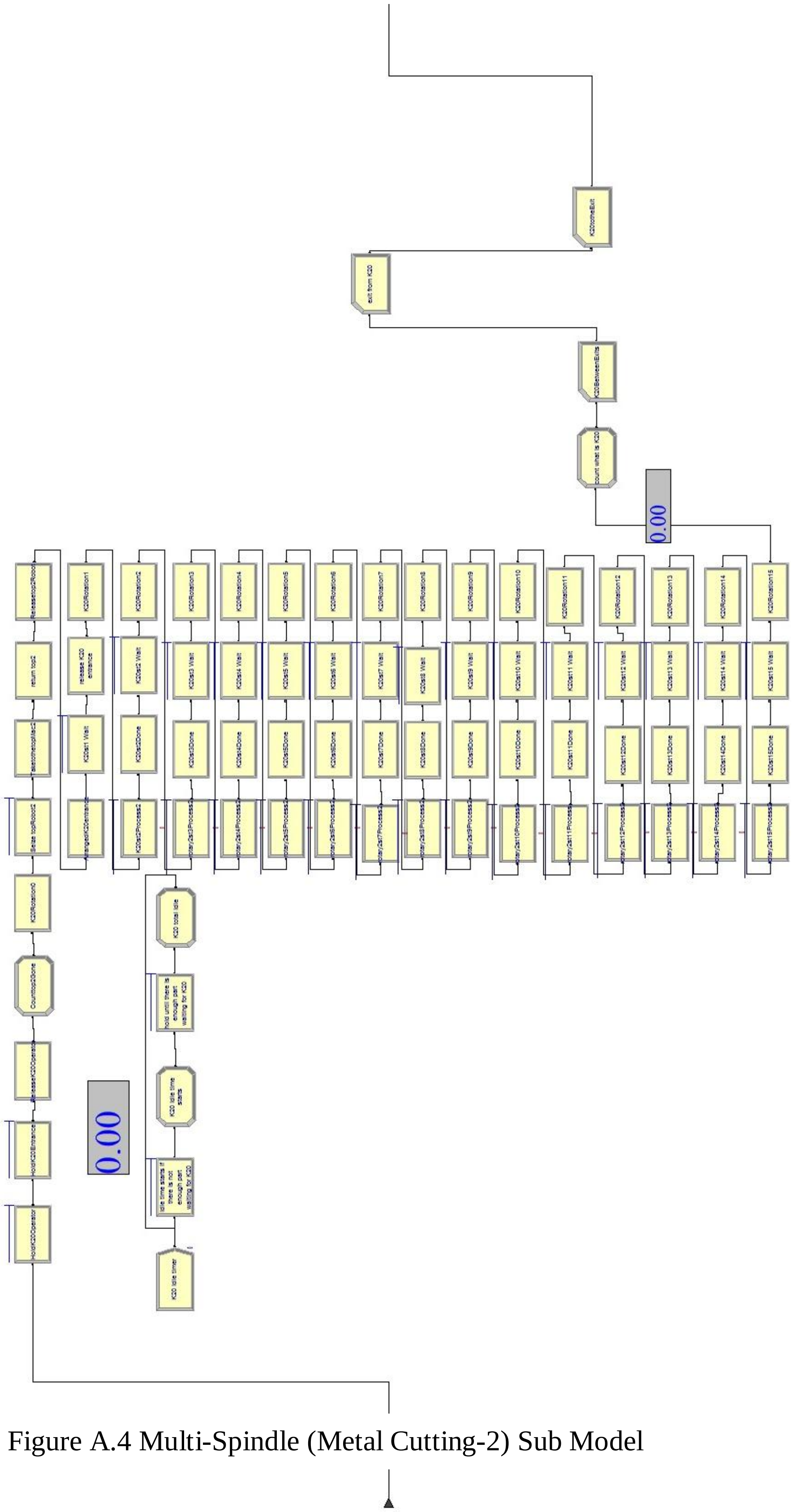


Figure A.4 Multi-Spindle (Metal Cutting-2) Sub Model

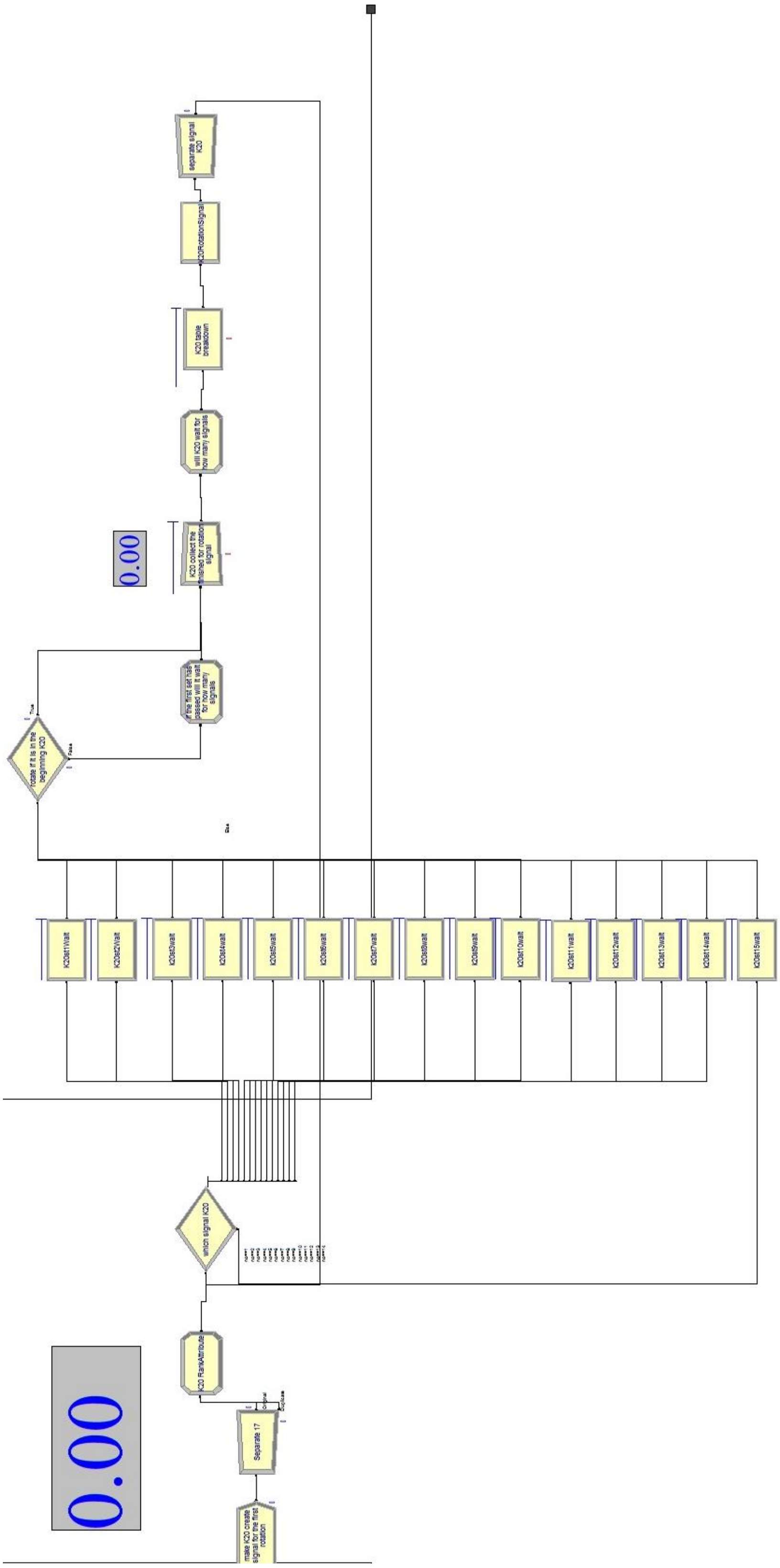


Figure A.5 Rotary Table Mechanism in Multi-Spindle (Metal Cutting-2) Sub Model

A.4. Sand Deburring Sub Model

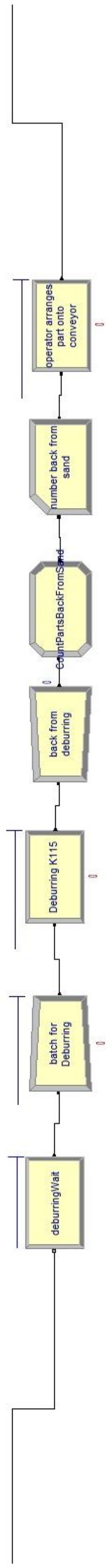


Figure A.6 Sand Deburring Sub Model

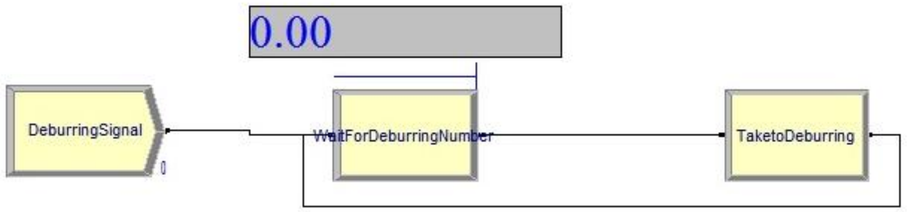


Figure A.7 Waiting Mechanism in Sand Deburring
Sub Model

A.5. Grinding-1 Sub Model

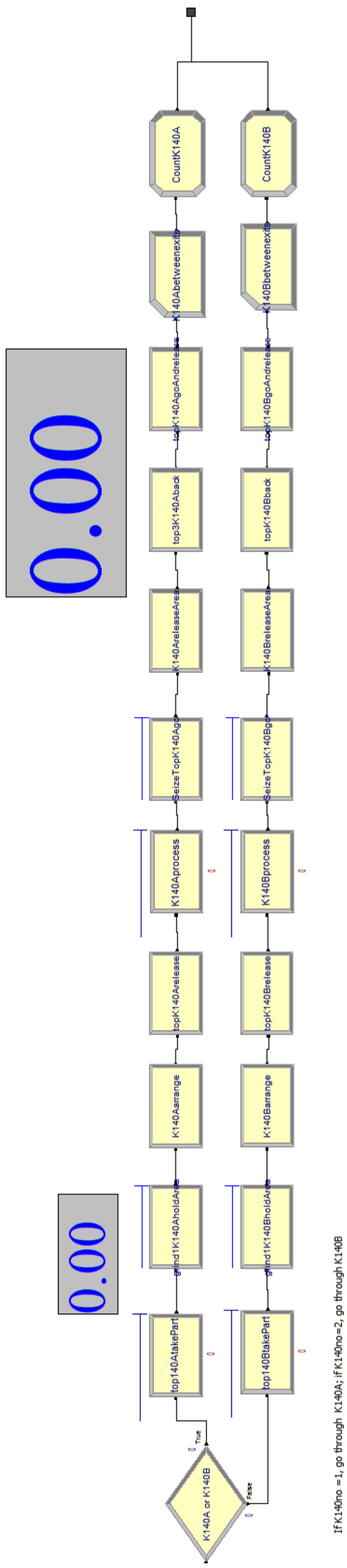


Figure A.8 Grinding-1 Sub Model

A.6. Marking Sub Model

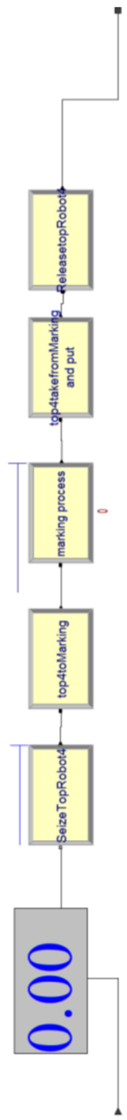


Figure A.9 Marking Sub Model

A.7. Grinding-2 Sub Model

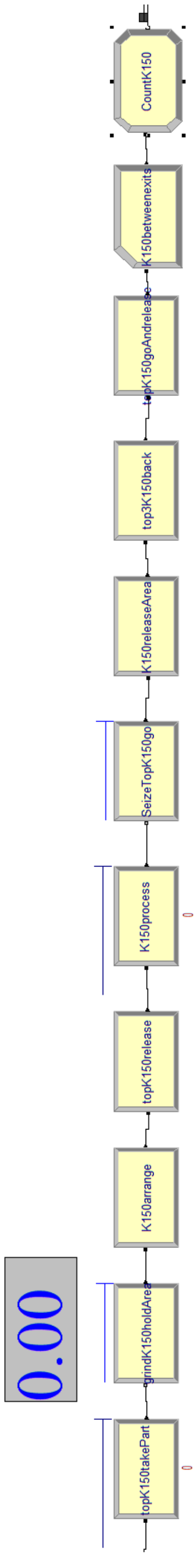


Figure A.10 Grinding-2 Sub Model

A.8. Grinding-3 Sub Model

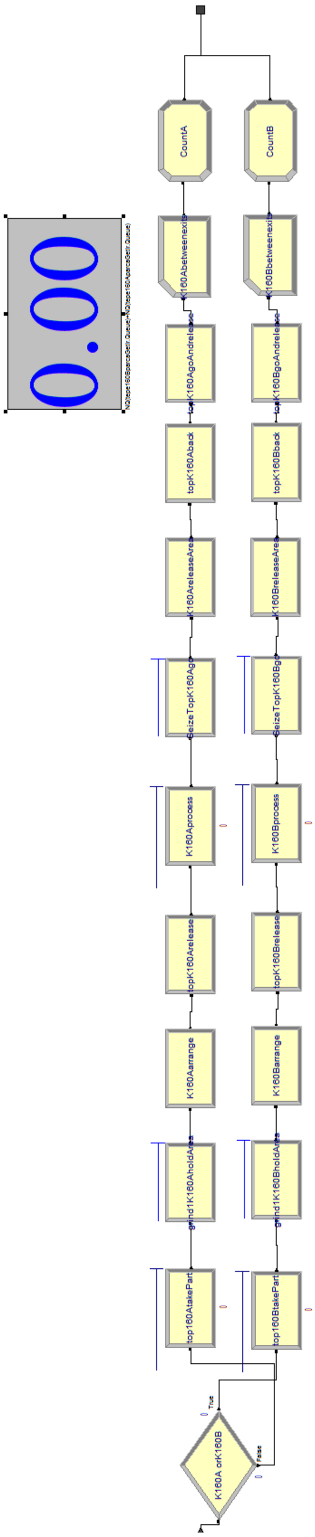


Figure A.11 Grinding-3 Sub Model

A.9. System Exit Sub Model

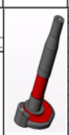
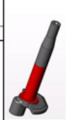
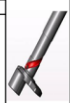
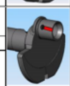
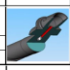
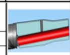
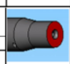
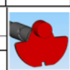
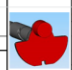
Figure A.12 System Exit Sub Model

APPENDIX B

AP 224 FEATURES OF CRANKSHAFT WITH ESTIMATED EMBODIED ENERGY

In the below Table, the features of Type-A crankshaft is given. In each feature, geometric and manufacturing parameters are listed. Using these parameters, Theoretical energy and the corresponding carbon emissions are estimated accordingly and displayed as follows:

Table B.1 AP 224 features of crankshaft with estimated embodied energy

		Geometric Param.	Manufacturing Param.	
Feature 1		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Outer Dia.		D_cast (mm)	a_f (mm/rev)	2.50
		D (mm)	γ_0	CO_2 (g)
		L (mm)	κ_r	0.37
		Vrem (mm3)	$k_{c1.1}$ (kJ/mm3)	
			mc	
			kc (kJ/mm3)	
			000-3	
Feature 2		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Tapered Outer Dia.		D_cast (mm)	a_f (mm/rev)	1.79
		D_cast_f (mm)	γ_0	CO_2 (g)
		D (mm)	κ_r	0.27
		D_f (mm)	$k_{c1.1}$ (kJ/mm3)	
		L (mm)	mc	
		α (Taper Angle)	kc (kJ/mm3)	
		Vrem (mm3)	000-3	
Feature 3		Geometric Param.	Manufacturing Param.	E_rh_t
STEP AP224: Outer Dia.		D_cast (mm)	a_f (mm/rev)	10.07
		D_rh_t (mm)	γ_0	E_fn_t
		D_fn_t (mm)	κ_r	0.62
		D (mm)	$k_{c1.1}$ (kJ/mm3)	E_gr
		L (mm)	mc	16.28
		V_rh_t (mm3)	kc_rh_t (kJ/mm3)	
		V_fn_t (mm3)	000-3, 000-4	
		V_gr (mm3)	a_f (mm/rev)	E_th (kJ)
			γ_0	26.97
			κ_r	CO_2 (g)
			$k_{c1.1}$ (kJ/mm3)	3.98
			mc	
			kc_fn_t (kJ/mm3)	
			000-9, 000-10	
			kc_gr (kJ/mm3)	
			005-2 (K140B - Koyo)	
Feature 4		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Square U Gr.		D (mm)	a_f (mm/rev)	1.18
		R (mm)	γ_0	CO_2 (g)
		W (mm)	κ_r	0.17
		α_1	$k_{c1.1}$ (kJ/mm3)	
		α_2	mc	
		r_1	kc (kJ/mm3)	
		r_2	000-5	
		V_rem (mm3)		
Feature 5		Geometric Param.	Manufacturing Param.	E_t
STEP AP224: NA		D_cast (mm)	a_f (mm/rev)	0.84
		L_cast (mm)	γ_0	E_gr
		D_t (mm)	κ_r	7.44
		L_t (mm)	$k_{c1.1}$ (kJ/mm3)	
		D (mm)	mc	
		L (mm)	kc_t (kJ/mm3)	E_th (kJ)
		V_t (mm3)	000-4, 000-5, 000-10	8.28
		V_gr (mm3)	kc_gr (kJ/mm3)	CO_2 (g)
			006 (K150 - Mecca1)	1.22
Feature 6		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Hole		D (mm)	Tool tip angle (α)	0.26
		L (mm)	kc (kJ/mm3)	CO_2 (g)
		Vrem (mm3)	000-61	0.04
Feature 7		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Hole		D (mm)	Tool tip angle (α)	0.07
		L (mm)	kc (kJ/mm3)	CO_2 (g)
		Vrem (mm3)	000-71	0.01
Feature 8		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Hole		D (mm)	Tool tip angle (α)	0.14
		L (mm)	kc (kJ/mm3)	CO_2 (g)
		Vrem (mm3)	000-72	0.02
Feature 9		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: NA		W (mm)	a_f (mm/rev)	0.32
		h (mm)	z	CO_2 (g)
		L (mm)	γ_0	0.05
		V_rem (mm3)	κ_r	
			$k_{c1.1}$ (kJ/mm3)	
			mc	
			kc (kJ/mm3)	
			000-62	
Feature 10		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: NA		D (mm)	a_f (mm/rev)	0.67
		R (mm)	z	CO_2 (g)
		W (mm)	γ_0	0.10
		α_1	κ_r	
		α_2	$k_{c1.1}$ (kJ/mm3)	
		r_1	mc	
		r_2	kc (kJ/mm3)	
		pitch	000-8	
		L		
		V_rem (mm3)		
Feature 11		Geometric Param.	Manufacturing Param.	E_rh_m
STEP AP224: Outer Dia.		D_cast (mm)	a_f (mm/rev)	0.00
		D_rh_m (mm)	z	E_rh_t
		D_rh_t (mm)	γ_0	5.84
		D_fn_t (mm)	κ_r	E_fn_t
		D (mm)	$k_{c1.1}$ (kJ/mm3)	0.30
		L (mm)	mc	E_gr
		V_rh_m (mm3)	kc_rh_m (kJ/mm3)	12.27
		V_rh_t (mm3)	001-2	
		V_fn_t (mm3)	a_f (mm/rev)	
		V_gr (mm3)	γ_0	E_th (kJ)
			κ_r	18.40
			$k_{c1.1}$ (kJ/mm3)	CO_2 (g)
			mc	2.72
E/M			kc_rh_t (kJ/mm3)	
			001-3	
			a_f (mm/rev)	
			γ_0	
			κ_r	
			$k_{c1.1}$ (kJ/mm3)	
			mc	
			kc_fn_t (kJ/mm3)	
			001-4	
			kc_gr (kJ/mm3)	
			007, 008	
Feature 12		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Hole		D (mm)	Tool tip angle (α)	1.37
		L (mm)	kc (kJ/mm3)	CO_2 (g)
		Vrem (mm3)	001-52,001-7	0.20
Feature 13		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Hole		D (mm)	Tool tip angle (α)	0.03
		L (mm)	kc (kJ/mm3)	CO_2 (g)
		Vrem (mm3)	001-6	0.00
Feature 14		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: NA		W (mm)	a_f (mm/rev)	0.01
		h (mm)	z	CO_2 (g)
		L (mm)	γ_0	0.00
		θ	κ_r	
		α_1	$k_{c1.1}$ (kJ/mm3)	
		α_2	mc	
		V_rem (mm3)	kc (kJ/mm3)	
			001-8	
Feature 15		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Hole		D (mm)	Tool tip angle (α)	0.13
		L (mm)	kc (kJ/mm3)	CO_2 (g)
		Vrem (mm3)	001-9, 001-10	0.02
Feature 16		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: Hole		D (mm)	Tool tip angle (α)	2.71
		L (mm)	kc (kJ/mm3)	CO_2 (g)
		Vrem (mm3)	2, 001-13, 001-14, 00	0.40
NA		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: NA		D (mm)	a_f (mm/rev)	1.60
		D_i (mm)	z	CO_2 (g)
		L (mm)	γ_0	0.24
		Vrem (mm3)	κ_r	
			$k_{c1.1}$ (kJ/mm3)	
			mc	
			kc (kJ/mm3)	
			001-12	
NA		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: NA		D_cast (mm)	a_f (mm/rev)	1.24
		L_alin (mm)	z	CO_2 (g)
		Vrem (mm3)	γ_0	0.18
			κ_r	
			$k_{c1.1}$ (kJ/mm3)	
			mc	
			kc (kJ/mm3)	
			001-2	
NA		Geometric Param.	Manufacturing Param.	E_th (kJ)
STEP AP224: NA		R_cast (mm)	a_f (mm/rev)	0.97
		L (mm)	z	CO_2 (g)
		Vrem (mm3)	γ_0	0.14
			κ_r	
			$k_{c1.1}$ (kJ/mm3)	
			mc	
			kc (kJ/mm3)	
			001-2	

APPENDIX C

SIMULATION OUTPUTS

Four alternative scenarios and three design alternatives have been proposed for the existing system (Type-A crankshaft production line). Each of them has been run and the outputs have been reported. The detailed discussion about the results is included in Chapter 3.

In addition, according to the objectives, comparison figures (comparison of each alternative scenario and design alternative in terms of objectives) are shown in the same Chapter. The reports of the simulation model run will be displayed as follows:

Table C.1 Type-A Existing System Output

Replications: 1 Time Units: Seconds

User Specified

Output

Output	Value
C_amortisation_	2.1141
C_directLabor_	0.0942
C_energy_	0.00
C_indirectLabor_	0.00
C_overall	2.2083
C_totalMaterial_	0.00
E_aux Metal Cutting1 out	310.69
E_aux Metal Cutting2 out	344.62
E_aux tot Grinding1_1 out	36.6790
E_aux tot Grinding1_2 out	64380.96
E_aux tot Grinding2 out	120.18
E_aux tot Grinding3_1 out	107.22
E_aux_idle Metal Cutting1 out	86.3251
E_aux_idle Metal Cutting2 out	100.43
E_aux_idle tot Grinding1_1 out	0.00
E_aux_idle tot Grinding1_2 out	0.00
E_aux_idle tot Grinding2 out	0.6997
E_aux_idle tot Grinding3_1 out	0.5136
E_aux_idle_total	188.26
E_aux_idle_totGrinding3_2 out	1.6829
E_aux_total	1098.83
E_aux_total_out	1098.83
E_aux_totGrinding3_2 out	608.02
E_deburring out	18.8033
Grinding1_1processNumber_	1949.22
Grinding1_1ProcessRate_out	0.9994
Grinding1_2processNumber_	1.1111
Grinding1_2ProcessRate_out	0.00056970
Grinding2processNumber_	1949.33
Grinding3_1processNumber_	1464.00
Grinding3_1ProcessRate_out	0.7524
Grinding3_2processNumber_	481.67
Grinding3_2ProcessRate_out	0.2476
Metal Cutting1processNumber_	1966.22
Metal Cutting2processNumber_	1965.44
numberBackfromDeburring	35200.00
PartperShift	1945.67
t_cycle_tot Grinding1_1 out	17.1719
t_cycle_tot Grinding3_1 out	22.8052
t_cycle_tot Grinding3_2 out	69.5580
t_cycle_totGrinding1_2 out	30240.00

Table C.2 Type-A Alternative Scenario-0 Output

Replications: 1 Time Units: Seconds

User Specified

Output

Output	Value
E_aux Metal Cutting1 out	290.59
E_aux Metal Cutting2 out	308.31
E_aux tot Grinding1_1 out	31.2280
E_aux tot Grinding1_2 out	**********.**
E_aux tot Grinding2 out	102.38
E_aux tot Grinding3_1 out	91.7285
E_aux_idle Metal Cutting1 out	66.2243
E_aux_idle Metal Cutting2 out	64.1118
E_aux_idle tot Grinding1_1 out	0.1193
E_aux_idle tot Grinding1_2 out	**********.**
E_aux_idle tot Grinding2 out	0.6962
E_aux_idle tot Grinding3_1 out	0.5128
E_aux_idle_tot Grinding3_2 out	1.6470
E_aux_idle_total	131.95
E_aux_tot Grinding3_2 out	512.93
E_aux_total	948.43
E_deburring out	18.8033
Grinding1_1processNumber_	1962.22
Grinding1_1ProcessRate	1.0000
Grinding1_2processNumber_	0.00
Grinding1_2ProcessRate	0.00
Grinding2processNumber_	1961.28
Grinding3_1processNumber_	1466.39
Grinding3_1ProcessRate	0.7498
Grinding3_2processNumber_	489.39
Grinding3_2ProcessRate	0.2502
Metal Cutting1processNumber_	1981.89
Metal Cutting2processRate_	1978.61
NumberBackfromDeburring	35420.00
PartperShift	1955.78
t_cycle_tot Grinding1_1 out	14.6119
t_cycle_tot Grinding1_2 out	0.00
t_cycle_tot Grinding2 out	14.5783
t_cycle_tot Grinding3_1 out	58.6534
t_cycle_tot Grinding3_1out	19.4947
t_idle Grinding1_1Grind out	0.06536806
t_idle Grinding1_2Grind out	**********.**
t_idle Grinding2Grind out	0.1060
t_idle Grinding3_1Grind out	0.1454
t_idle Grinding3_2Grind out	0.1955
t_idle Metal Cutting1 stAll	4.0389

Table C.3 Type-A Alternative Scenario-1 Output

Replications: 1   Time Units: Seconds

User Specified

Output

Output	Value
E_aux Metal Cutting1 out	290.59
E_aux Metal Cutting2 out	308.31
E_aux tot Grinding1_1out	31.2280
E_aux tot Grinding1_2 out	**********.**
E_aux tot Grinding2 out	102.38
E_aux tot Grinding3_1 out	91.7285
E_aux_idle Metal Cutting1 out	66.2243
E_aux_idle Metal Cutting2 out	64.1118
E_aux_idle tot Grinding1_1 out	0.1193
E_aux_idle tot Grinding1_2 out	**********.**
E_aux_idle tot Grinding2 out	0.6962
E_aux_idle totGrinding3_1 out	0.5128
E_aux_idle_tot Grinding3_2 out	0.1171
E_aux_idle_total	131.57
E_aux_tot Grinding3_2 out	256.49
E_aux_total	884.26
E_deburring out	18.8033
Grinding1_1processNumber_	1962.22
Grinding1_1ProcessRate	1.0000
Grinding1_2processNumber_	0.00
Grinding1_2ProcessRate	0.00
Grinding2processNumber_	1961.28
Grinding3_1processNumber_	1466.39
Grinding3_1ProcessRate	0.7498
Grinding3_2processNumber_	489.39
Grinding3_2ProcessRate	0.2502
Metal Cutting1processNumber_	1981.89
Metal Cutting2CalismaOran	0.9474
Metal Cutting2processNumber_	1978.61
NumberBackfromDeburring	35420.00
PartperShift	1955.78
t_cycle_tot Grinding1_1 out	14.6119
t_cycle_tot Grinding1_2 out	0.00
t_cycle_tot Grinding2 out	14.5783
t_cycle_tot Grinding3_1 out	19.4947
t_cycle_tot Grinding3_2 out	29.4105
t_idle Grinding1_1Grind out	0.06536806
t_idle Grinding1_2Grind out	**********.**
t_idle Grinding2Grind out	0.1060
t_idle Grinding3_1Grind out	0.1454
t_idle Grinding3_2Grind out	0.01390283

Table C.4 Type-A Alternative Scenario-2 Output

Replications: 1 Time Units: Seconds

User Specified

Output

Output	Value
E_aux Metal Cutting1 out	290.59
E_aux Metal Cutting2 out	308.31
E_aux tot Grinding1_1 out	31.2280
E_aux tot Grinding1_2 out	**********.**
E_aux tot Grinding2 out	102.38
E_aux tot Grinding3_1 out	91.7285
E_aux_idle Metal Cutting2 out	64.1118
E_aux_idle tot Grinding1_1 out	0.1193
E_aux_idle tot Grinding1_2 out	**********.**
E_aux_idle tot Grinding2 out	0.6962
E_aux_idle tot Grinding3_1 out	0.5128
E_aux_idle_tot Grinding3_2 out	0.1171
E_aux_idle_total	131.57
E_aux_idleMetal Cutting1 out	66.2243
E_aux_tot Grinding3_2 out	256.49
E_aux_total	884.26
E_deburring out	18.8033
Grinding1_1processNumber_	1962.22
Grinding1_1ProcessRate	1.0000
Grinding1_2processNumber_	0.00
Grinding1_2ProcessRate	0.00
Grinding2processNumber_	1961.28
Grinding3_1processNumber_	1466.39
Grinding3_1ProcessRate	0.7498
Grinding3_2processNumber_	489.39
Grinding3_2ProcessRate	0.2502
Metal Cutting1processNumber_	1981.89
Metal Cutting2processNumber_	1978.61
NumberBackfromDeburring	35420.00
PartperShift	1955.78
t_cycle_tot Grinding1_1 out	14.6119
t_cycle_tot Grinding1_2 out	0.00
t_cycle_tot Grinding2 out	14.5783
t_cycle_tot Grinding3_1 out	19.4947
t_cycle_tot Grinding3_2 out	29.4105
t_idle Grinding1_1Grind out	0.06536806
t_idle Grinding1_2Grind out	**********.**
t_idle Grinding2Grind out	0.1060
t_idle Grinding3_1Grind out	0.1454
t_idle Grinding3_2Grind out	0.01390283
t_idle Metal Cutting1 stAll	4.0389

Table C.5 Type-A Alternative Scenario-3 Output

Replications: 1 Time Units: Seconds

User Specified

Output

Output	Value
E_aux Metal Cutting1 out	288.36
E_aux Metal Cutting2 out	305.32
E_aux tot Grinding1_1 out	30.7441
E_aux tot Grinding1_2 out	**********.**
E_aux tot Grinding2 out	100.76
E_aux tot Grinding3_1 out	91.1483
E_aux_idle Metal Cutting1 out	63.9944
E_aux_idle tot Grinding1_1 out	0.1170
E_aux_idle tot Grinding1_2 out	**********.**
E_aux_idle tot Grinding2 out	0.6854
E_aux_idle tot Grinding3_1 out	0.5096
E_aux_idle_tot Grinding3_2 out	0.1298
E_aux_idle_total	126.33
E_aux_idleMetal Cutting2 out	61.1263
E_aux_tot Grinding3_2 out	244.15
E_aux_total	874.66
E_deburring out	18.8033
Grinding1_1processNumber_	1993.11
Grinding1_1ProcessRate	1.0000
Grinding1_2processNumber_	0.00
Grinding1_2ProcessRate	0.00
Grinding2processNumber_	1992.89
Grinding3_1processNumber_	1475.72
Grinding3_1ProcessRate	0.7416
Grinding3_2processNumber_	514.11
Grinding3_2ProcessRate	0.2584
Metal Cutting1processNumber_	2009.89
Metal Cutting2CalismaOran	0.9474
Metal Cutting2processNumber_	2009.11
PartBackfromDeburring	36080.00
PartperShift	1989.83
t_cycle_tot Grinding1_1 out	14.3857
t_cycle_tot Grinding1_2 out	0.00
t_cycle_tot Grinding2 out	14.3470
t_cycle_tot Grinding3_1 out	19.3714
t_cycle_tot Grinding3_2 out	27.9941
t_idle Grinding1_1Grind out	0.06411417
t_idle Grinding1_2Grind out	**********.**
t_idle Grinding2Grind out	0.1044
t_idle Grinding3_1Grind out	0.1445
t_idle Grinding3_2Grind out	0.01540523

Table C.6 Design Alternative “Type-B” Output

Replications: 1 Time Units: Seconds

User Specified

Output

Output	Value
E_aux Metal Cutting1 out	320.26
E_aux Metal Cutting2 out	361.18
E_aux tot Grinding1_1 out	37.9700
E_aux tot Grinding1_2 out	**********.**
E_aux tot Grinding2 out	124.48
E_aux tot Grinding3_1 out	108.55
E_aux_idle Metal Cutting1 out	88.0206
E_aux_idle Metal Cutting2 out	94.8419
E_aux_idle tot Grinding1_1 out	0.1243
E_aux_idle tot Grinding1_2 out	**********.**
E_aux_idle tot Grinding2 out	0.7256
E_aux_idle tot Grinding3_1 out	0.5200
E_aux_idle_tot Grinding3_2 out	1.8885
E_aux_idle_total	184.55
E_aux_tot Grinding3_2 out	682.31
E_aux_total	1102.56
E_aux_total out	1102.56
E_deburring out	18.8033
Grinding1_1processNumber_	1882.94
Grinding1_1ProcessRate_out	1.0000
Grinding1_2processNumber_	0.00
Grinding1_2ProcessRate_out	0.00
Grinding2processNumber_	1882.06
Grinding3_1processNumber_	1446.11
Grinding3_1ProcessRate_out	0.7711
Grinding3_2processNumber_	429.22
Grinding3_2ProcessRate_out	0.2289
Metal Cutting1processNumber_	1906.44
Metal Cutting2processNumber_	1898.67
PartBackfromDeburring	34100.00
PartperShift	1875.33
t_cycle_tot Grinding1_1 out	17.7763
t_cycle_tot Grinding1_2 out	0.00
t_cycle_tot Grinding2 out	17.7423
t_cycle_tot Grinding3_1 out	23.0873
t_cycle_tot Grinding3_2 out	78.0569
t_idle Grinding1_1Grind out	0.06812026
t_idle Grinding1_2Grind out	**********.**
t_idle Grinding2Grind out	0.1105
t_idle Grinding3_1Grind out	0.1474
t_idle Grinding3_2Grind out	0.2242

Table C.7 Design Alternative “casting” Output

Replications: 1 Time Units: Seconds

User Specified

Output

Output	Value
E_aux Metal Cutting1 out	305.84
E_aux Metal Cutting2 out	339.56
E_aux tot Grinding1_1 out	36.0108
E_aux tot Grinding1_2 out	**********.**
E_aux tot Grinding2 out	118.19
E_aux tot Grinding3_1 out	106.38
E_aux_idle Metal Cutting1 out	85.4086
E_aux_idle Metal Cutting2 out	97.5812
E_aux_idle tot Grinding1_1 out	0.1178
E_aux_idle tot Grinding1_2 out	**********.**
E_aux_idle tot Grinding2 out	0.6887
E_aux_idle tot Grinding3_1 out	0.5096
E_aux_idle_tot Grinding3_2 out	1.6055
E_aux_idle_total	184.58
E_aux_tot Grinding3_2 out	584.95
E_aux_total	1046.03
E_aux_total_out	1046.03
E_deburring out	18.8033
Grinding1_1processNumber_	1985.39
Grinding1_1ProcessRate_out	1.0000
Grinding1_2processNumber_	0.00
Grinding1_2ProcessRate_out	0.00
Grinding2processNumber_	1982.17
Grinding3_1processNumber_	1475.56
Grinding3_1ProcessRate_out	0.7467
Grinding3_2processNumber_	500.67
Grinding3_2ProcessRate_out	0.2533
Metal Cutting1processNumber_	1999.50
Metal Cutting2processNumber_	1998.72
NumberBackfromDeburring	35860.00
PartperShift	1976.22
t_cycle_tot Grinding1_1 out	16.8591
t_cycle_tot Grinding1_2 out	0.00
t_cycle_tot Grinding2 out	16.8463
t_cycle_tot Grinding3_1 out	22.6266
t_cycle_tot Grinding3_2 out	66.9199
t_idle Grinding1_1Grind out	0.06452864
t_idle Grinding1_2Grind out	**********.**
t_idle Grinding2Grind out	0.1049
t_idle Grinding3_1Grind out	0.1445
t_idle Grinding3_2Grind out	0.1906

Table C.8 Design Alternative "Spindle Stop& Optimization" Output

Replications: 1 Time Units: Seconds

User Specified

Output

Output	Value
E_aux Metal Cutting1 out	306.04
E_aux Metal Cutting2 out	333.56
E_aux tot Grinding1_1 out	36.3989
E_aux tot Grinding1_2 out	**********.**
E_aux tot Grinding3_1 out	107.26
E_aux totGrinding2 out	119.34
E_aux_idle Metal Cutting1 out	85.9116
E_aux_idle Metal Cutting2 out	99.91
E_aux_idle tot Grinding1_1 out	0.00
E_aux_idle tot Grinding1_2 out	**********.**
E_aux_idle tot Grinding2 out	0.6950
E_aux_idle tot Grinding3_1 out	0.5138
E_aux_idle_tot Grinding3_2 out	1.6390
E_aux_idle_total	187.31
E_aux_tot Grinding3_2 out	592.17
E_aux_total	1043.88
E_aux_total_out	1043.88
E_deburring out	18.8033
Grinding1_1processNumber_	1964.22
Grinding1_1ProcessRate_out	1.0000
Grinding1_2processNumber_	0.00
Grinding1_2ProcessRate_out	0.00
Grinding2processNumber_	1963.06
Grinding3_1processNumber_	1463.50
Grinding3_1ProcessRate_out	0.7474
Grinding3_2processNumber_	494.56
Grinding3_2ProcessRate_out	0.2526
Metal Cutting1processNumber_	1981.28
Metal Cutting2processNumber_	1980.44
NumberBackfromDeburring	35420.00
PartperShift	1958.06
t_cycle_tot Grinding1_1 out	17.0409
t_cycle_tot Grinding1_2 out	0.00
t_cycle_tot Grinding2 out	17.0104
t_cycle_tot Grinding3_1 out	22.8130
t_cycle_tot Grinding3_2 out	67.7452
t_idle Grinding1_1Grind out	0.06507975
t_idle Grinding1_2Grind out	**********.**
t_idle Grinding2Grind out	0.1058
t_idle Grinding3_1Grind out	0.1457
t_idle Grinding3_2Grind out	0.1946

APPENDIX D

INFORMATION ABOUT RESEARCH FIELDS IN REFERENCES

In the Table in this Appendix, the survey papers, articles, power point slides of researchers, have been listed in terms of their content related with the Thesis subject such as:

- Sustainable manufacturing (related with energy efficiency, green manufacturing, e.t.c.),
- Simulation,
- Optimization (simulation-based and multi-objective),

The stars filled in the boxes of the table shows the paper (or article, power point presentation slides, e.t.c.) that has been investigated reflects the content with the star. For instance, Antonio A. et al. (2007) have done research about sustainable manufacturing.

Table D.1 Information about Research Fields in References

			OPTIMIZATION	
References	SUSTAINABLE MANUFACTURING	SIMULATION	Simulation-based	Multi-objective
Environment and Development",1992	***			
Antonio A. et al., 2007	***			
Former U.S. Senator Gaylord Nelson, 1996	***			
Manufacturing Technology Platform Theme: Sustainable Manufacturing, 2008	***			
Silvia Leahu- Aluas, 2010	***			
Hibbard S., 2009	***			
Gök G., 2012	***			
"Waste Minimization", 2013	***			
"Waste Minimization Plan", 2011	***			
V. Veleva et al., 2001	***			
D. Krajnc, P. Glavic, 2003	***			
"2005 Environmental Sustainability Indicators", 2005	***			
"Indicators of sustainable development: Guidelines and Methodologies", 2007	***			

Table D.1 (continued)

References	SUSTAINABLE MANUFACTURING	SIMULATION	OPTIMIZATION	
			Simulation-based	Multi-objective
"Sustainable Manufacturing and Eco-Innovation: Framework, Practices and Measurement", 2009	***			
Marler et al., 2004				***
Zhou et al. (2013)		***		***
Adinarayana et al. (2014)				***
Kelton W., 2008		***		
J. Carson and D. Brunner (2000)		***		
Hosseinpour F. et al., 2009		***		
Park S. et al., 2006		***		
J. Banks (2000)		***		
Law (1999)		***		
Law and McComas (1991)		***		
Rahimifard and Seow (2011)		***		
Rahimifard et al. (2010)		***		
Kara et al. (2011)		***		
Scriber T. J., 1991		***		
Azadeh (2010)		***		
Patel et al (2002)		***		
Choi et al. (2002)		***		
Potoradi et al. (2002)		***		
Kibira et al. (2002)		***		
Altiparmak et al. (2002)		***		
Wiendahl et al. (1991)		***		

Table D.1 (continued)

References	SUSTAINABLE MANUFACTURING	SIMULATION	OPTIMIZATION Simulation-based	OPTIMIZATION Multi-objective
Carson et al. (1997)		***	***	
Bowden et al., 1998			***	
Hall et al. (1998)			***	
Azadivar (1992)			***	
Glynn (1989)			***	
Reiman and Weiss (1986)			***	
Morrice and Schruben, 1989			***	
Schruben and Cogliano, 1987			***	
Holland, 1992			***	
Shahabuddin, 1995			***	
Huerta-Barrientos et al. (2014)			***	
Apak and Ercan (2012)		***		
Caputo et al. (2009)		***		
Herrmann et al. (2009)		***		
Melouk et al. (2013)		***	***	
Law et al. (2002)				
Matta (2008)				
Zhu et al. (2014)				
Dao-fei et al. (2010)		***	***	
Rani et al. (2010)		***	***	
Othman et al. (2012)		***		
Shadiya et al. (2012)	***	***		***
Glover et al., 1996		***		

Table D.1 (continued)

References	SUSTAINABLE MANUFACTURING	SIMULATION	OPTIMIZATION Simulation-based	OPTIMIZATION Multi-objective
Gurkan et al. (2005)		***		
Williams (2002)		***		
Rogers (2002)		***		
Altinkilic (2004)		***		
Chen (2002)		***		
Köse (2003)		***		
Hill (2001) and Standridge (1991)		***		
Graves and Higgins (2002)		***		
Dennis et al. 2000		***		
Nsakanda and Turcotte (2004)		***		
Law and Kelton 1991		***		
Hammann (1995)		***		
Liu et al. (2012)				
Zein et al. (2012)				
Dietmair and Verl (2009)				
Guo and the others (2012)				
Babu et al. (2012)				
Liu et al. (2012)				
Driussi and Jansz (2006)	***			
Begum et al. (2006)	***			
Brinksmeier et al. (1998)				
Editorial, 2014		***		
Fu, 2002			***	
Eskandari et al. (2011)			***	
Batz, M., (2007)			***	
Willis et al. (2008)			***	
Singarvela et al. (2014)				***
Heilala et al. (2008)		***		