TRADE-OFF MODELS IN SUSTAINABLE SYSTEMS ENGINEERING

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ABSTRACT

TRADE-OFF MODELS IN SUSTAINABLE SYSTEMS ENGINEERING

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Prior to concerns of sustainability, almost all industrial engineering models tried to minimize cost or maximize profit. Sustainability awareness has recently forced the decision makers to also take into consideration such aspects as clean water use, or carbon dioxide emissions. In an effort to incorporate more aspects of sustainability in optimizing production efforts, we present a network model to handle trade-offs among dissimilar sustainability criteria. Since typically there are alternative choices for the various operations, the network allows parallel arcs between the same nodes. We also introduce the concept of *generalized cost*. Generalized cost is a vector quantity that includes not only a monetary measure, but also measures relevant to sustainability, such as carbon use or embodied energy. The approach leads to a multi-criteria decision making model, whose efficient frontier is obtained by the epsilon constraint method. Numerical work shows that the computational effort to obtain the efficient frontier is reasonable, allowing products of up to about a hundred activities to be solved with the current generation of personal computers.

Keywords: Sustainability, Trade-off

ÖZ

SÜRDÜRÜLEBİLİR SİSTEMLER MÜHENDİSLİĞİNDE ÖDÜNLEŞİM MODELLERİ

Özaslan, Mustafa Onur

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Sürdürülebilirlik ile ilgili endişelerden önce neredeyse bütün endüstri mühendisliği modelleri, maliyetleri minimize etmek veya kârı maksimize etmek üzerineydi. Sürdürülebilirlik bilinci, karar vericiyi temiz su kullanımı veya karbondioksit salınımı gibi konuları da dikkate almaya yöneltti. Sürdürülebilirliğin üretim modellerinde yer alması noktasında, farklı sürdürülebilirlik kriterlerinin vazgeçişlerinin bulunduğu ağ modelleri sunuyoruz. Farklı operasyonlar için farklı alternatifler olduğundan ağ modelimiz iki nokta arasında paralel oklara izin vermektedir. Bunun yanında genelleştirilmiş maliyet kavramı modellere entegre edilmektedir. Genelleştirilmiş maliyet vektörü sadece parasal maliyetleri değil aynı zamanda sürdürülebilirlik ile ilişkili karbon kullanımı veya enerji tüketimi gibi ölçütleri de kapsamaktadır. Bu yaklaşımın sonucu olarak, çok amaçlı karar verme modeli ortaya çıkmıştır. Bu modelin etkili çözümleri epsilon kısıt yöntemi ile belirlenmektir. Sayısal örnekler, 100 aktiviteye kadar olan modellerin etkili çözümlerin günümüz kişisel bilgisayarlarıyla kabul edilebilir bir sürede oluşturulabildiğini göstermiştir.

Anahtar Kelimeler: Sürdürülebilirlik, Ödünleşim

To my family

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CHAPTER 1

INTRODUCTION

1.1. Sustainability

"Sustainability" has recently become quite a popular topic, especially after the so-called financial crisis of 2008. The events of fall 2008 led to increased fuel and energy prices, which in turn created intensified interest in sustainability. There are other adjectives used in this regard, such as green, renewable, and environment friendly.

The term "sustainability" is usually given with reference to the work of the United Nations World Commission on the Environment and Development of 1983. The resultant report, published in 1987 [1], *Our* C*ommon Future,* is perhaps better known as the Bruntland Report. The report defines sustainable development as follows:

> “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”

Some would argue, however, that the concept of sustainable development is an oxymoron; Allenby & Richards [2], Jickling [3], Tryzna [4], Benyus [5], Hawken *et al*. [6], von Weizsacker *et al*.[7]; since no development can actually be accomplished without the accompanying degradation of the environment.

The Bruntland Report definition is good for popular science and for the purposes of media. All can relate to the intergenerational contract outlined by the definition. In fact, most would interpret "future generations" as their offspring, for whom they would care. However, from an engineering perspective, the Bruntland Report definition of sustainability is not quite operational. It may be more productive to consider different definitions of sustainability that are pertinent to environmental, economic, and social cycles. If these cycles are to be sustainable, there should be a well balanced no accumulation or no depletion. Currently, many of these cycles are not so. Clearly, there is an accumulation of greenhouse gases in the atmosphere, owing to the extensive use of fossil fuels. Similarly, the fresh water resources are being depleted. These are but the most visible of the imbalances of cycles.

There are other ways to view sustainability. This thesis is set in an industrial engineering background. For our purposes, it suffices to view sustainability as the awareness to reduce, if not eliminate the environmental load of engineering activities. In most general terms, we consider manufacturing and service operations and seek alternatives that contrast the various objectives of profit against the reduction of environmental load.

1.2. Economics and Sustainability

In free-market economics, one considers the cost and benefit of undertaking a certain activity. The concept of economic equilibrium indicates that supply and demand will eventually be balanced. That is, if the marginal cost of a good or service is less than its benefit, there will be more demand, and thus, supply will rise accordingly. Similarly, if the marginal cost is higher, the demand will fall, since the free market will view that product or service as being overpriced. The current difficulty with this view is that so far, it has implicitly been assumed that the cost of a product or service does not include the environmental impact. For instance, in a foundry operation, we ignore the cost of carbon released into the atmosphere. If one were to add the cost of environmental load, then the equilibria that held hitherto may no longer be valid. In effect, this would mean that virtually all products and services considered to have settled at their free-market values are under-priced. Increasing the cost should reduce demand. Unlike direct costs such as labor or materials, the mechanisms to incorporate the cost of environmental impact are not fully in place. The well-known Kyoto Protocol, for instance, attempts to put a price on the emission of greenhouse gases by introducing a cap-and-trade system [8]. The cost of emitting carbon dioxide from industrial operations will thus be incorporated into the cost of the manufactured products. Although this is quite reasonable in theory, a viable operational system of trade is yet to be established. Some further argue that it would be futile to adopt the same free-market models that brought us to the brink of environmental collapse to try to remedy its ill-effects.

This thesis is not so ambitious as to address the issue of how world economics should be structured to improve sustainability. Instead, we develop techniques to give decision makers quantitative tools to assist in selecting a suitable alternative among a given set. Almost always, there are trade-offs among these alternatives. For example, one may reduce greenhouse gases at the expense of increased manufacturing costs, or reduce pollution at the expense of increased materials cost.

1.3. Sustainability Measures and Indicators

If we are to improve sustainability, we must first quantify it. In some sense, sustainability may be viewed as a binary proposition. The human activities in their totality may either be sustainable or not, rather than assuming various levels of sustainability. This view is perhaps logically and scientifically more sound. However, if we are to change our habits, it becomes operationally more useful to view at least aspects of sustainability on a grade scale. This way, we could measure the direction and magnitude of our efforts in terms of how it impacts those aspects.

There are several measures of sustainability. More indirectly than the measures, one also finds many indicators of sustainability. Since global climate change considered to be a direct outcome of the greenhouse gases emitted in the process of energy generation [9], the energy content of products and services attract attention. The amount of energy needed to produce that product or service is called embodied energy, or emergy for short. For instance, there is quite a lot of energy needed to produce aluminum from ore. Since aluminum is melted during the process, the energy requirements are high. Although most of us are not sensitive to this energy content, nonetheless, one could view virtually all products and services to incorporate an energy component.

Similarly, we could take any of the natural resources and consider each product or service in terms of how much of that resource it contains. Most notably, one may consider how much water is needed to produce that service or product. This indirect water content is referred to as virtual water.

Below is a short list of products and their embodied energy and contents.

Table 1 Embodied Energy Values for Some Materials*

Material	Energy (MJ/kg)	Carbon (kg CO2 / kg)	Density (kg / m3)
Aggregate	0.1	0.005	2240
Bricks (common)	3	0.22	1700
Concrete block (150mm medium weight)	0.71	0.08	1900
Steel (virgin)	35.3	27426	7800
Steel (recycled)	18507	0.43	7800
Steel (typical virgin/recycled)	24.4	28126	7800
Aluminum (general & incl. 33% recycled)	155	45505	2700
Glass	15	0.85	2500
Iron (general & average)	25	33239	7870

**http://www.greenspec.co.uk/html/materials/embodied_energy.html*

It was mentioned that economic models to date very seldom include the costs of environmental resources. In a typical trade-off effort, it is usually the cases that lower natural resource requirements of products and services may be attained using more elaborate technologies. This, in turn, usually corresponds to higher costs. So the trade-off is typically between, say lower cost versus lower emergy.

1.4. An Overview of this Thesis

Our work focuses on the trade-offs inherent in many decision making situations concerning aspects of sustainability. Most often, we find trade-offs between lower cost of manufacturing versus lower emissions of greenhouse gases. The emission of greenhouse gases is typically a result of the energy needed to manufacture the product. Hence, there usually is a strong correlation between greenhouse gas emissions and the embodied energy of the product. The embodied energy may be reduced if high technology manufacturing processes are adopted. This, in turn, however, increases the current production cost. Lowering both manufacturing costs and emergy requires a shift in technology. Such technological advances are the only true solutions in the long run. However, currently, some trade-offs may be needed to prevent further global environmental degradation.

We use activity networks to model a manufacturing process. Alternative steps of the manufacturing process are recorded on the network, along with the cost and emergy requirements of each alternative. We desire to eliminate those combinations of steps that lead to both high cost and high emergy. In this sense, our model may be viewed as a multi-criteria optimization model. Note that emergy is not the only possible sustainability measure. Virtual water was mentioned. Such diverse measures as social impact or likeliness to alter disease vectors may also be considered. Similarly, we also consider time to manufacture, or make-span, as another performance measure. Make-span considerations, however, impose a fundamentally different structure on the model.

1.5. Past Work on Models of Sustainable Systems

Being a relatively new subject to industrial engineering, there is a paucity of past work. There is however, quite an accumulation of related studies, which we summarize below. The consideration of sustainability constraints on classical production models basically started with considering the carbon emission as cost (or tax). Most of operations research models are cost oriented.

Hartl *et al*.[10] worked on *optimal input substitution of a firm facing environmental constraints*. Their model imposes environmental constraints either using cleaner inputs or by changing (improving) production technologies. They also propose a remarkable conclusion: “if there is no economic incentive for voluntary substitution or environmental tax, the firm will not use clean input (as long as it is expensive) and if the emission amount is determined based on total capacity of the firm, it can choose to leave some capacity instead of using clean output.”

Subsequently, Dobos [11] modified the Holt-Modigliani-Muth-Simon (HMMS) model to investigate how environmental policies, in the form of emission charges or emission limits, affect the production-inventory decision of a firm. In his work *Production-inventory control under environmental constraints*, he writes *“A linear unit pollution charge in the HMMS model reduces the production rate and the inventory level. And environmental standards reduce the range of production possibilities. As a consequence, a firm must produce more and longer along an interior production path in order to compensate for this deficit in supply.”*

Next, Dobos [12] extended his work to the Arrow-Karlin model. He modified the Arrow-Karlin model to introduce the effects of the emission charges and emission standards to production strategies in *Production strategies under environmental constraints in an Arrow-Karlin model.* He there submits another proposition “*The firm will not change its optimal production strategy if its production level does not reach maximum allowable emission.”*

Dobos [13] introduced a component of environmental awareness into production models by governmental pollution costs and limit constraints in his 2001 work

*Production strategies under environmental constraints: Continuous-time model with concave costs***.** This time he states his proposition as "*The environmental policy of the government is ineffective, if the linear charge per unit pollution is smaller than* τ_1 or *larger than* τ_2 *(where are* τ_1 *&* τ_2 *determined by firms own production model).*"

Pindyck [14] worked on the timing of environmental policy decisions in *Optimal timing problems in environmental economics*. He stated three important characteristics that environmental problems have;

- *There is almost always uncertainty over the future costs and benefits of adopting a particular policy.*
- *There are usually important irreversiblities associated with environmental policy*
- *Policy adaptation is rarely a now or never proposition; in most cases it is feasible to delay action and wait for new information.*

He proposed that a policy could be adopted now, or later or never. What makes the decision complex is uncertainties in the future. In addition, tomorrow might be too late for taking action.

Yalcinoz & Koksoy [15] worked on Power and Energy systems in *A multi-objective optimization method to environmental economic dispatch.* Their first suggestion is to weight cost and emission figures. "*Methods of multi-objective optimization can be classified in many ways according to different criteria*". Hwang and Masud classify the methods according to participation of the decision maker in the solution process. The classes are:

- *Methods where no articulation of preference information is used (no-preference methods)*
- *Methods where a posteriori articulation of preference information is used (a posteriori methods)*
- *Methods where a priori articulation of preference information is used (a priori methods)*

- *Methods where progressive articulation of preference information is used (interactive methods)*

The idea of the MPB (Multi-objective Proximal Bundle) is to move in a direction where the values of all the objective functions improve simultaneously.

The same year, Masui [16] carried out his work, *Policy evaluations under environmental constraints using a computable general equilibrium model*, on the AIM / Material model. He has shown that the introduction of low-emission vehicles as a CO_2 reduction policy produces a negative effect on the waste management problem. He also demonstrated that the Japanese GDP would decrease by 0.2% in 2010, if Japan reaches the objectives put forth by the KYOTO CO_2 protocol.

In 2006, Radulescu et al. [17] has studied production models in *Sustainable production technologies which take into account environmental constraints* where the pollution is considered to be a probabilistic event. He formulated multi-product models to maximize the return in two different approaches. In the first approach, a firm pays as much as its risk, and in the second, charges are based on realization.

Peter Letmathe et al.[18], presented two mathematical models that can be used by firms to determine their optimal product mix and production quantities in the presence of several different types of environmental constraints, in addition to the typical production constraints. Their models were based on the assumption that there is a market in which firms may trade their emission allowance.

CHAPTER 2

AN ILLUSTRATIVE EXAMPLE

Prior to presenting formal trade-off models, we offer an example to introduce the elements of our study with the hope of motivating the reader. In this example, we study the open-faced Turkish meat pie or pizza, known as "lahmacun" (see Figure 1). One of the major reasons to choose lahmacun as an example is its interesting history. There is hardly any difference in the manufacture of lahmacun through the eons. It can be said that people of past centuries made and ate lahmacun just about the same way it exists today. Small lahmacuns are often served in meat restaurants as appetizers. Larger lahmacuns, usually along with a salad, may be eaten as lunch or a light supper. The Middle East Technical University food courts make lahmacun in a wood-fired stone oven to achieve maximum culinary appeal in taste and texture.

A lahmacun is estimated to provide about 250 to 300 dietary calories (250 to 300 kilocalories or kcals). The production of lahmacun, however consumes much more energy than its dietary value. We now examine the emergy (embodied energy) of lahmacun and compare it to its dietary value. Moreover, we consider a few alternatives in the production of lahmacun. These alternatives are compared according to their cost and emergy values.

Figure 1 Lahmacun

2.1. Data Gathering

Since lahmacun is a composite product, we first collect cost and emergy information about its constituents. The methods explained in this section are adopted by the subsequent analysis in model building. Our models are based on activity networks. Accordingly, in this example, we introduce a simplified activity flow network. The network depicts only the four main ingredients of lahmacun for brevity. These main ingredients are flour, onion, tomato, and minced meat. These ingredients account for about 80% of lahmacun’s weight but 99% of its emergy value. The remainder of the weight is almost all water. An extended ingredients list is given in the Appendix A.

2.2. Activity Flow Networks

The activity flow network of lahmacun is next constructed. Similarly, for the sake of brevity and simplicity, most of the processes are grouped. While choosing which processes to merge, energy consumption is taken into account. The simplified activity network is given below in Figure 2. As seen we adopt the “Activity on Arc” (AoA) convention.

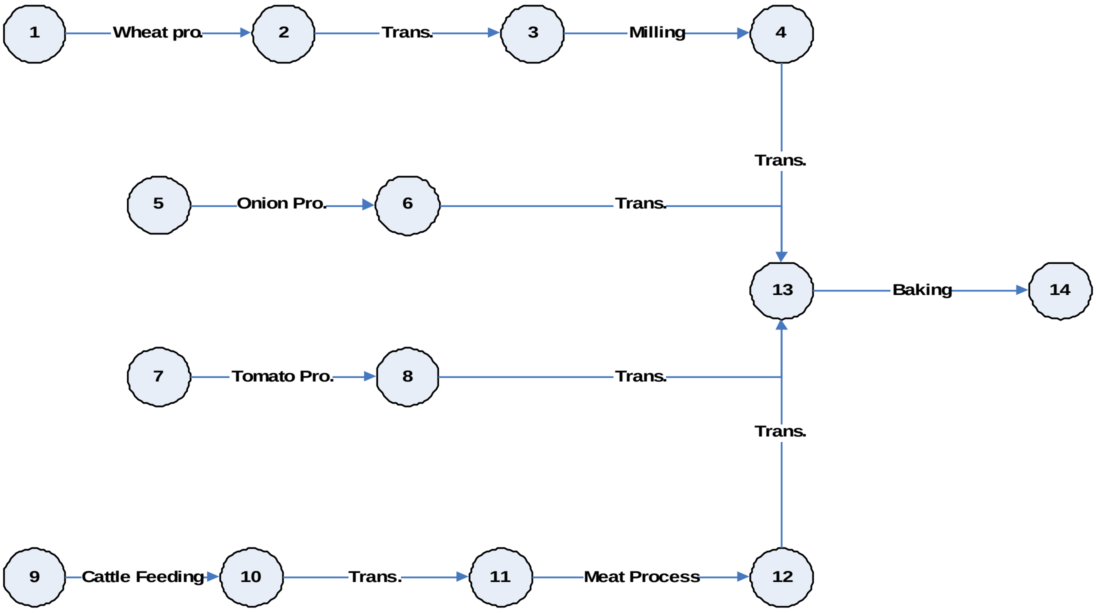

Figure 2 Flow Network of Lahmacun

Typically, there are many alternatives for each activity. For instance, the transportation of wheat (arc 2-to-3) may be by truck or by rail. These alternatives are called modes. This term is inspired by the project management literature, where alternatives to activities are also called “modes.” Take, for instance, the activity 3-4 “wheat flour milling.” It can be carried out by numerous different mills of different locations, technologies, and capacities. The cost, the energy spent and the scrap rate for each type of mill are likely to differ.

Gathering data for cost and scrap rate figures is easy compared to obtaining emergy figures. As the topic is relatively new, there are no universally accepted methodologies to calculate emergy. Instead, there are some approaches presented for evaluating emergy. One of the most prominent approaches is the input-output analysis, which is presented by Costanza [19]. Input-output analysis is a kind of deductive methodology. For instance, instead of calculating emergy of one kg wheat, the energy input for the entire land is calculated and divided by the total yield.

On the other hand, it is possible to calculate the exact energy input for some activities, like baking in an electrical oven.

2.3. Caloric Efficiency

Caloric Efficiency is defined as the amount of emergy obtained by consuming a product (lahmacun) as a ratio of the amount energy spent to produce it. Hence it resembles output-to-input ratio. Appendix A gives a thorough list of emergy and scrap rates for each mode of each activity for the simplified lahmacun model. From this data, it is possible to deduce how much emergy is consumed to make lahmacun as it is made at the METU food court, and most probably, as it was made throughout the centuries. The calculations (see Appendix A) reveal that 7080 Kcal is spent to make a single lahmacun in this fashion. Considering that one can get only 250 Kcal by consuming a lahmacun, the output-to-input ratio, or caloric efficiency is around 3.53 %. This level of inefficiency, only around four percent, is quite surprising to most consumers.

2.4. Alternate Modes

The lahmacun is sold for 2 TL (about $1.25) at the food court. You may increase the caloric efficiency by choosing some other alternatives. In other words, the amount of emergy spent may be decreased, hence the caloric efficiency (of about 3.5%) may be increased. For example, suppose there is a new transportation mode that uses an advanced fuel. The fuel produces half the CO_2 but costs about twice as much as petroleum-based fuels. The same activity network given in Figure 2 can be used to compute the cost and emergy of lahmacun produced in this fashion. According to Appendix A2, energy spent for the transportation for a lahmacun is around 92.7 kcal.

Let us say the transportation cost is 0.2 TL (10% of its price). The results are given below.

Table 2 Simple Comparison of Alternative Modes

Fuel	Cost of the transportation per lahmacun	Emergy per lahmacun
Petroleum-based	0.2 TL	7080 Kcal
Advanced	0.4 TL	7033.7 Kcal

As one can see, the two alternatives cannot readily be compared to determine which is better. Each alternative is better than the other in one of the criteria. A common approach to resolving such preferences is based on attaching a price to the non-monetary items. In this case, following the KYOTO protocol [8] approach to charge CO_2 emissions, on could convert the emergy valued to CO_2 equivalents, and add the cost to the price of the product. In essence, this approach attaches weights to all criteria and allows the decisions to be based on the cumulative or aggregate cost alone. The difficulty with this approach is in how the costs or weights are assigned. For instance, what is the price of a species going extinct? Or the price to finding contaminants in the blood of newborns?

Then a more reasonable approach is trade-off analysis. In Chapter 3, we will discuss models structured to observe trade-offs between cost and emergy.

CHAPTER 3

EMERGY/COST TRADE-OFF MODELS

We almost always are faced with trade-offs. The analysis of the options and their implications of the various possible trade-offs is the primary subject of this thesis. In its most general form, we are presented with alternatives and a set of economic and sustainability measures for each alternative. If an alternative would score higher on all performance measures, it would clearly be the preferred and selected one. However, as it happens in almost *all* cases, different alternatives score higher in different performance measures as we illustrated in the previous chapter for cost and emergy. The concept of a “best alternative” is thus not applicable.

Before we delve deeper into the models, let us introduce the concept of generalized cost, which will be used in all our models.

3.1. Generalized Cost

Generalized cost is a term which was first used by people who study supply chain economics. It could be defined as a combination of monetary and non-monetary cost items. In its most common form, the monetary item represents money where the non-monetary item is time. The basic form of generalized cost is as follows:

$$g = c + f(t)$$

Since, all monetary items can easily be converted to each other, they are represented by a single parameter c. The function f (t) transforms the value of time into the monetary items.

In this study, the generalized cost is used to combine different types of environmental indicators. We use an array for cost items as they cannot be merged into single parameter.

$$g \overset{\Delta}{=} c$$

In this chapter, network flow trade-off models will be investigated for two cases: linear and discrete. The models select one or more modes for each activity, i.e. they are mode selection models.

3.2. Linear Emergy/Cost Trade-Off Models

Our first model is for the linear mode selection case. The model allows fractional mode assignments. For instance, the wheat producer can transport one third of its yield by truck and the remaining by rail. We now present the mathematical formulation of the linear trade-off model by describing its decision variables, parameters, constraints and objective function.

Decision Variables

X_{ijm} = amount of flow between nodes i and j, i.e., activity i-j) by mode m (if there is scrap in the activity, it represents the input quantity)

Parameters

c_{ijm} = unit cost of performing activity i-j by mode m

c^{m}_{ijm} = monetary cost item of the cost array of activity i-j and mode m

c^{e}_{ijm} = emergy item of the cost array of activity i-j and mode m

α_{ijm} = 1- scrap rate of activity i-j in mode m

β_{ij} = amount of activity i-j that is needed by a unit activity starting from node j. It is not mode specific, i.e. same for all modes of activity i-j.

The following variables will be used in our models, when some of the resources are capacitated. These extensions will be discussed more specifically in the constraints section below.

L^{e} = global emergy limit for entire process

L^{m} = global cost limit (or budget) for entire process.

L^{e}_{ij} = emergy limit for activity i-j

L^{m}_{ij} = cost limit for activity i-j

Constraints

Demand Constraints

In the process path, these types of constraints represent the requirement relationships among activities. Two types of processes could occur among nodes: sequential and sub-assembly. **Sequential processes** are basically among two consecutive activities of a serial flow, as depicted by Figure 3 below

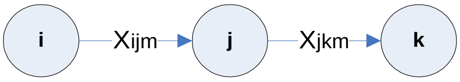

Figure 3 Sequential Processes

Note from the figure that activity j-k requires the output of the activity i-j. Constraint set (1) represents the sequential flows mathematically.

$$\sum_m \alpha_{\mathrm{ijm}} * X_{ijm} \geq \sum_m X_{jkm} \quad \textit{for all (i-j) and (j-k) that are connected serially} \; (1)$$

Wheat production and wheat milling well present the sequential processes. The scrap ratio is around ¼, i.e. $\alpha_{\mathrm{ijm}} = 0.75$. Therefore, wheat production, i.e. $\sum_m X_{ijm}$, should be more than flour 1.33 times the flour production, i.e. $\sum_m X_{jkm}$.

Sub-Assembly Processes can be of two types: sub-assembly merge processes (and type relations) and sub-assembly alternate processes (or type relations).

i. Sub-Assembly Merge

In Sub-assembly merge processes, outputs or two more activities are required for the successor activity, as depicted by the following figure.

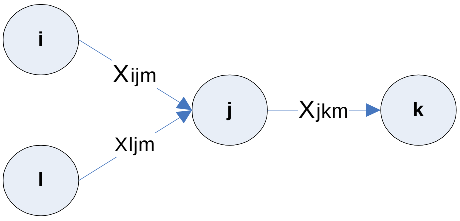

Figure 4 Sub- Assembly Processes

Note that activity j-k requires the outputs of activity i-j and activity l-j

We must also specify the amount of each sub-assembly required to obtain the successor intermediate product. We introduce the parameter β, the amount of activity that is needed by the successor activity. For instance, to prepare 1 lahmacun, we need 100 gr. or 0.1 kg of meat. This follows β = 0.1 as we take kg for meat flow measure. Consequently, the constraint for sub-assembly processes is written as follows.

$$\sum_{m}(\alpha_{\mathrm{ijm}} * X_{ijm}) \geq \beta_{\mathrm{ij}} * \sum_{m} X_{jkm}$$ *for all (i-j) and (j-k) such that (i-j) is required for (j-k)* (2-a)

As stated, the parameters β do not depend on the mode.

i. Sub-Assembly Alternate

In Sub-assembly alternate processes, any subset of the outputs of two or more activities may be used by the successor activity. Here we make a decision as to how much of which sub-assembly to use in order to produce the successor product. As an example, consider the case where we could make lahmacun with lamb or beef, or with some combination of the two types of meat. Then, we only need a single constraint to ensure the flow of conservation.

$$\sum_{m} \sum_{(i,j)\in S_{jk}}(\alpha_{ijm} * X_{ijm}) \geq \sum_{m} X_{jkm} \qquad \text{(2-b)}$$

Limit Constraints

We may have some restrictions on some cost items for a particular activity or for the entire process. We refer to these as capacitated models. For instance, there are a lot of fertilizer restrictions for EU countries or there could be CO_2 restrictions for entire process after Kyoto protocol is fully implemented. Otherwise, it is also possible to have some budget for a particular activity or entire network. Following constraints helps to integrate these types of restrictions to our model.

$$\sum_{m}(c^{m}{}_{ijm} * X_{ijm}) < L^{m}{}_{ij} \text{ = Budget constraint for activity i-j} \quad (3)$$

$$\sum_{i}\sum_{j}\sum_{m}(c^{m}{}_{ijm} * X_{ijm}) < L^{m} \text{ = Budget constraint for entire network} \quad (4)$$

$$\sum_{m}(c^{e}{}_{ijm} * X_{ijm}) < L^{e}{}_{ij} \text{ = Local energy limit for activity i-j} \quad (5)$$

$$\sum_{i}\sum_{j}\sum_{m}(c^{e}{}_{ijm} * X_{ijm}) < L^{e} \text{ = Global energy limit} \quad (6)$$

Note that none of limit constraints are introduced to our lahmacun example.

The Objective Function

Our objective in this model is to minimize cost and the emergy jointly.

$$\mathrm{f}_1(\mathrm{x}) = \sum_{i}\sum_{j}\sum_{m}(c^{m}{}_{ijm} * X_{ijm})$$

$$\mathrm{f}_2(\mathrm{x}) = \sum_{i}\sum_{j}\sum_{m}(c^{e}{}_{ijm} * X_{ijm})$$

Hence, we have a Multi Criteria Decision Making (MCDM) problem with two objectives. MCDM discipline has a lot of powerful techniques to handle bi-objective models. It is possible either to generate a solution with the help of priori knowledge on the decision maker’s priorities or by interacting with the decision maker. In the next section, we discuss our solution methods.

Solutions

In this section, we first discuss the concepts of MCDM that are pertinent to our study. We then present our application with concerns of sustainability issues.

3.2.1. MCDM Problems

In sustainability studies, we are often content with just a few criteria. In fact, considering merely cost and emergy provides significant insights into most problems of sustainability. In cases where there are only a few objectives, the well-known Epsilon Constraint Method (ECM) is an expedient and pragmatic choice to solve MCDM models. In this thesis, we used the ECM to gain insights into the computational difficulty of out models. As it will be presented in the following chapters, our model requires little computational effort compared to many other types of MCDM models. For the test problems studied in this thesis, we had no need to seek solution procedures other than the ECM.

Before presenting with the ECM methodology, we introduce some definitions. The definitions and the methodology are stated for the two criteria.

Definitions

We give the definitions for a bi-objective optimization problem. The definitions could be generalized to multi-objective problems.

min $f(x) = (f_1(x),f_2(x))$ subject to x Є X (where X is the set of feasible solutions)

1. **Dominant solution:** let x_1 and x_2 Є X. A solution x_1 is said to be dominating x_2 $(x_1\ x_2)$, if and only if $f_1(x_1) <= f_1(x_2)$ and $f_2(x_1) <= f_2(x_2)$, with strict inequality holding at least once
2. **Pareto Efficiency:** A solution x_1 is said to be Pareto efficient if and only if there is no solution dominates it.
3. **Efficient Set,** E: A set that contains all the Pareto efficient points. E = {x Є X: x is Pareto efficient in X }.
4. **Pareto Front,** F: A set that contains all the Pareto efficient solutions F = {f(x): x Є E}.

Recall that, we do not convert emergy to cost and minimize the total cost. In effect, emergy and cost are handled as independent peer criteria. Therefore, we create Pareto efficient solutions and leave the final trade-off decision to the decision maker.

Two extreme points in the solution set will be the minimum cost and the minimum emergy points. In addition to these two, some (and usually all) Pareto efficient solution between these two solutions will be generated by the ECM.

We next state the ECM.

The Epsilon Constraint Method

The epsilon constraint method (ECM) is one of the most powerful tools in the MCDM discipline. The ECM is proposed by Chankong and Haimes [20] in 1983. The model is:

$\min f_k(x)$

subject to $f_i(x) \leq \varepsilon_i$ ($i \neq k$)

$x \in E$

where ε_i is a vector ($\varepsilon_{-k} = (\varepsilon_1, \varepsilon_2 \ldots \varepsilon_{k-1}, \varepsilon_{k+1} \ldots \varepsilon_n)$) and ε_i's are chosen such that feasibility is not violated.

An alternate approach is given below.

$\min f_k(x) + \varepsilon * f_i(x)$

s. t. $f_i(x) \leq k$

$[\, f_k^*(x), f_i^*(x)] \rightarrow k = f_i^*(x)-1$

And then repeat the process until the solution is infeasible or a known lower bound on $f_i(x)$ is reached

Chankong and Haimes stated two theorems about the ECM

Theorem 1 *for any* $\varepsilon_{-k} \in IR^{n-1}$

If $x \in X$ *is an unique optimal solution of* $P\varepsilon_{-k}$*, then x is properly efficient solution*

Theorem 2 *A solution* $x \in X$ *is efficient*

If and only if it is an optimal solution of $P\varepsilon_{-k}$ *for every* $k=1.2\ldots n$ *where* $\varepsilon_{-i} = fi(x)$ *for* $i = 1.2\ldots.n$ $i \neq k$

Based on the first theorem, it is possible to generate an algorithm to create the Pareto efficient points. First we will find the minimum cost solution (C_m*), and the corresponding emergy value (C_m*). A step size ε of emergy is chosen. We add a new upper bound (constraint) on emergy $(C_E*-\varepsilon)$. With this additional constraint, a new solution is found. This new solution will have a lower emergy than the original minimum cost solution. However, the cost of the new solution will be higher than the minimum cost solution. These two solutions already display a emergy/cost trade-off.

Step I *Find min monetary cost* (C_m*), *(environmental cost is free)*

Step II *Find corresponding Emergy value* (C_E*) *and add a constraint*

$$(\sum_i \sum_j \sum_m c^e_{ijm} * X_{ijm} \leq C_E)$$

Step III *Change rhs value as* $C_E*-\varepsilon$ *and find new solution*

In this fashion, it is possible to generate more efficient solutions. As the ECM is extremely powerful, it is possible to generate the exact Pareto front for the decision maker. However, for large sized models, especially for those that are also NP-hard, deriving the exact Pareto front is difficult. It is possible to use a small scalar rather than ε, which will result in a subset of efficient points instead of the exact Pareto front.

Prior to solution the process, it may be possible to reduce the model is size to simplify the solution effort. In the next section, the mode elimination technique will be discussed.

Mode Elimination

Mode elimination is done by considering the so-called dominating modes.

Definition: A mode m_1 dominates mode m_2 of a given activity if and only if m_1 is better in each cost index.

$$c_{ijm_2} \geq c_{ijm_1} \text{ \textit{(at least one strict inequality holds)}}$$

Note that for all trade-off models in this thesis, scrap rates are defined for each activity. In some cases, a dominated mode can be non-dominated after multiplying the cost items by the corresponding scrap rate (α). Hence, we must take care of this fact and eliminate mode k in activity i-j only if there exists a mode t such that,

$$c_{ijk} * \alpha_{ijk} \geq c_{ijt} * \alpha_{ijt}$$

After eliminating the dominated modes, we can start the solution process of the reduced formulation. It is the hope that reducing the number of modes also reduces computational effort, and thus justifies the extra step of scanning the modes and removing the dominated ones.

The Minimum Cost Solution

In order to obtain the minimum cost solution, the objective function is set to:

$$\min \sum_i \sum_j \sum_m c^m{}_{ijm} * X_{ijm}$$

As our cost and emergy values are continuous, the resulting solution is strictly efficient, i.e. no solution has better cost value. If our cost parameters were discrete, the solution might not be efficient. To handle this, after finding the minimum cost solution (c_1*), we could fix the cost value $\sum_i \sum_j \sum_m c^m{}_{ijm} * X_{ijm} \leq c_1^*$ and find the minimum of emergy values corresponds to c_1* value.

The Minimum Emergy Solution

Similar to the previous part, to get the least emergy solution the objective function is:

$$\min \sum_i \sum_j \sum_m c^e{}_{ijm} * X_{ijm}$$

For the minimum emergy solution, similar to previous part, to handle efficiency problem, we would add $\sum_i \sum_j \sum_m c^e{}_{ijm} * X_{ijm} \leq E_2^*$, where E_2* is the minimum emergy, and find the minimum of cost values corresponds to E_2* value.

Efficient Solutions Generated

Since the model is linear, there are infinitely many feasible solutions, the classical version of the ECM cannot be applied. Instead, we will try to generate a meaningful subset of the efficient solutions. Subsequent to generating the minimum cost (c_1*, E_1*) and the minimum energy solution (c_2*, E_2*), we will take minimum cost solution as a starting point and then try to improve the energy need of the model.

We use of the objective function of the minimum cost solution and add the new constraint

$$\sum_i \sum_j \sum_m c^e{}_{ijm} * X_{ijm} \leq E_1^* - \phi$$

With this constraint, the emergy consumption will be reduced by φ. Then in each step, the φ value will be increased. φ is chosen to be 5%, 10%, 20%, 40%, 60% and 80% of difference between best (E_2*) and worst (E_1*) energy values.

This methodology generates the approximate efficient frontier, and a subset of exact efficient solutions. The approximation would be improved as one uses more φ values with smaller step sizes.

3.3. Discrete Mode Trade-Off Models

In this part, we will investigate the case where exact one mode is selected for each activity. For instance, wheat may be either transported by truck or by rail, but not by combination of the two.

Decision Variables

We define a binary (zero-one) decision variable Y_{ijm} as follows:

$$Y_{ijm} = \begin{cases} 1 \text{ if mode m is selected for activity i - j} \\ 0 \text{ otherwise} \end{cases}$$

Note that previous decision variable X_{ijm} is dependent on Y_{ijm}. Such that $X_{ijm} > 0$ only if Y_{ijm}.=1. The X_{ijm}s are necessary due to presence of α_{ijm} and β_{ij} values.

Constraints

Beside the constraints process needs (1), (2) and limit constraints (3), (4), (5) and (6), the following additional constraints will be added.

This constraint ensures that only one mode could be selected for any given activity.

$$\sum_{m} Y_{ijm} = 1 \qquad \text{for every i-j} \qquad (6)$$

The following constraints ensure that X_{ijm} takes value zero if Y_{ijm} is zero, where M is a big number; M needs to be at least as large as the upper bound on the value of X_{ijm}.

$$Y_{ijm} * M \geq X_{ijm} \qquad \text{for every i-j and m} \qquad (7)$$

Objective Function

Like its linear counterpart, the objective is to minimize cost and emergy jointly.

$$\mathrm{f}_1(\mathrm{x}) = \sum_i \sum_j \sum_m (c^m{}_{ijm} * X_{ijm})$$

$$\mathrm{f}_2(\mathrm{x}) = \sum_i \sum_j \sum_m (c^e{}_{ijm} * X_{ijm})$$

Merely minimizing $f_1(x)$ gives us the minimum cost solution, while minimizing $f_2(x)$ gives us the minimum emergy solution. While we iterate through the ECM, we minimize cost and progressively restrict the emergy value. If a solution cannot be found, then we relax the emergy constraint. The least emergy value so obtained corresponds to minimizing $f_2(x)$.

Efficient Solutions

We minimize $f_1(x)$ to obtain the minimum cost solution of the discrete trade-off formulation.

After generating the minimum cost solution, the ECM is applied to the model. Adding the following constraint generates next ECM solution.

$$\sum_i \sum_j \sum_m c^e{}_{ijm} * X_{ijm} \leq E_1^* - \varepsilon \qquad (8)$$

Unlike the linear model, there are finitely many efficient solutions and all of them could be obtained by updating E_1* incrementally. The Pareto front curve is obtained once all the efficient solutions are generated.

CHAPTER 4

COMPUTATIONAL EXPERIENCE FOR EMERGY/COST TRADE-OFF MODELS

In this chapter, we design an experiment to gain insights into the problem and to verify the developed models. Five synthetic examples, CE1 to CE5, are generated. These examples were generated to provide different network topologies in order to gain further insights into the computational aspects of the solution technique.

CE1 consist of 20 activities and its network topology is familiar to the lahmacun example. The network scheme for CE1 example is demonstrated below.

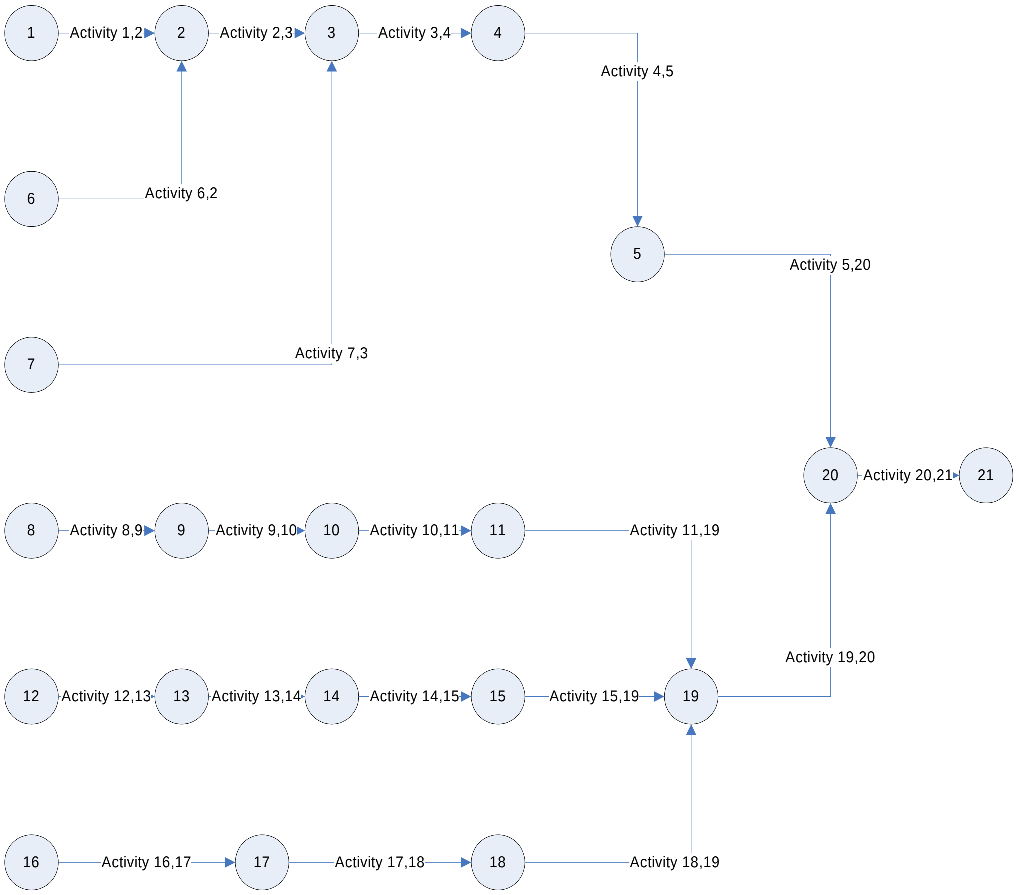

Figure 5 CE1 Network Scheme

In all sub-assembly relationships of CE1, we prefer to have merge type of relationships.

For each activity of CE1, a random number of modes, between 2 and 4, are generated by the Excel random number generator function. Similarly, costs, emergy, scrap rates (α) and assembly ratios (β) are generated by Excel. All data are given in Appendix B.

Solution sets of CE1 will be given here, whereas those of other examples (CE2 to CE5) are placed in Appendix B.

Before starting the solution process, all dominated modes are eliminated as it is explained in Chapter 3. It is seen that 21 out of 59 modes are eliminated for CE1. The eliminated modes are given in Table 3 below.

Table 3 Eliminated Modes in CE1 for Emergy /Cost Trade-off Model

Activity	Mode	Activity	Mode
1-2	c	12-13	d
6-2	a	13-14	b
6-2	d	13-14	c
7-3	b	13-14	d
4-5	b	15-19	a
8-9	b	15-19	c
9-10	c	16-17	c
10-11	c	18-19	a
11-19	c	19-20	a
11-19	d	20-21	a
12-13	c		

After reducing the problem size by mode elimination, we start generating the solutions in next section.

4.1. Linear Emergy/Cost Trade-Off Solutions

The Minimum Cost Solution

The solution is **\$17.046.** It corresponds to an emergy value of **5412.83** kcal. (c_1*, E_1*) = (17.046, 57412.83).

The Minimum Energy Solution

The solution is **3061.48** kcal and corresponds to a monetary cost figure of **$34.040**. ($c_1$*, E_1*) = (33.040, 3061.48).

Efficient Solutions Generated

We use φ values of 5%, 10%, 20%, 40%, 60% and 80%. For first iteration, (E_1* - φ1) equals to 5295.27 kcal. Then, new cost is equal to $17.124. Similarly, other five efficient solutions are generated and the cost and emergy values are presented in Table 4.

Table 4 Efficient Solutions Generated

Φ	Cost	Emergy
Minimum Cost	17.046	5412.83
5%	17.124	5295.27
10%	17.203	5177.70
20%	17.360	4942.56
40%	18.712	4472.29
60%	20.732	4002.02
80%	24.658	3531.75
Minimum Emergy	34.040	3061.48

After the subset of the exact efficient set is created, the frontier curve is drawn as in Figure 6.

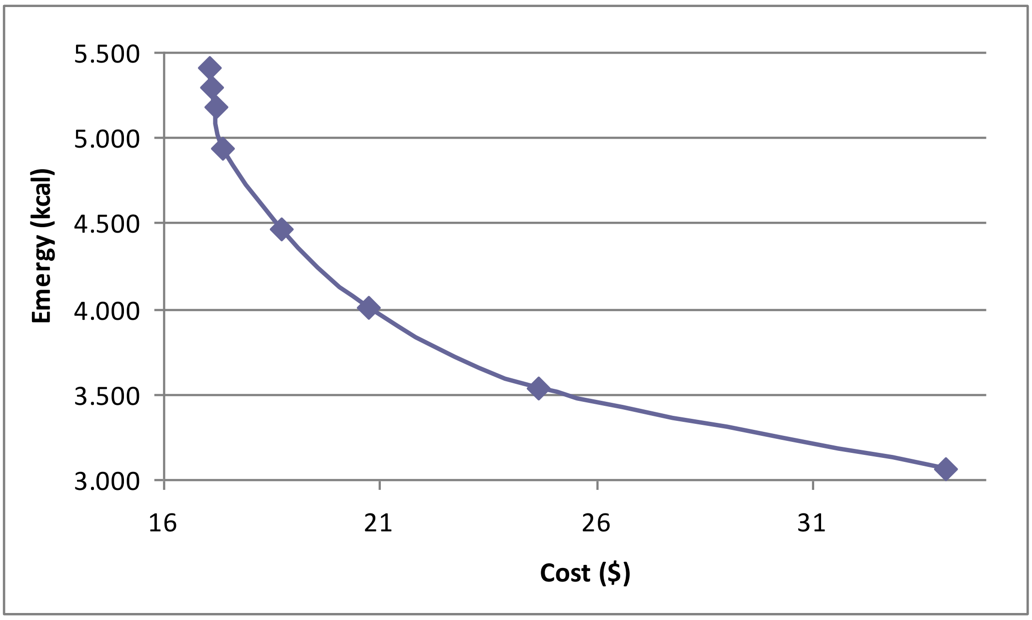

Figure 6 An Approximate Frontier Curve for Linear Solutions, Model CE1

As a first impression, in the first iteration, the emergy value is improved 2.17% whereas the cost is increased by only 0.46%. However, for the last iteration, to gain a 13.32% improvement in emergy, cost has to be increased by 38.05%. In common sense terms, one may claim that the initial steps towards sustainability seem to be cheaper.

4.2. Discrete Emergy/Cost Trade-Off Solutions

The Minimum Cost Solution

The solution has a cost value of **$17.046** and corresponding energy value is **5412.834** kcal.

Efficient Solutions Generated:

After the minimum cost solution is obtained, the related constraint (8) is inserted into the model. “ε” is set to be 0.1. Then, in each iteration, a new efficient solution is generated. Table 5 lists all efficient points generated by this way.

Table 5 Efficient Solutions Generated by ECM

Iteration	Cost	Emergy	Iteration	Cost	Emergy
step_1	17.046	5412.83	step_55	21.838	3830.25
step_2	17.240	5398.54	step_56	22.123	3817.23
step_3	17.255	5359.40	step_57	22.352	3815.85
step_4	17.416	4858.23	step_58	22.503	3787.24
step_5	17.610	4843.94	step_59	22.697	3772.95
step_6	17.625	4804.80	step_60	22.712	3733.81
step_7	17.792	4791.58	step_61	22.879	3720.59
step_8	17.832	4789.58	step_62	22.919	3718.59
step_9	17.959	4782.09	step_63	23.046	3711.10
step_10	18.015	4766.12	step_64	23.101	3695.13
step_11	18.025	4733.84	step_65	23.112	3662.86
step_12	18.032	4675.82	step_66	23.290	3652.76
step_13	18.226	4661.53	step_67	23.456	3647.16
step_14	18.241	4622.39	step_68	23.530	3619.11
step_15	18.407	4609.17	step_69	23.874	3603.42
step_16	18.447	4607.17	step_70	24.222	3594.61
step_17	18.574	4599.68	step_71	24.388	3589.01
step_18	18.630	4583.71	step_72	24.462	3560.96
step_19	18.641	4551.44	step_73	24.806	3545.27
step_20	18.683	4480.99	step_74	25.459	3544.46
step_21	18.877	4466.69	step_75	25.694	3531.67
step_22	18.892	4427.55	step_76	25.979	3518.65
step_23	19.058	4414.33	step_77	26.208	3517.27
step_24	19.098	4412.34	step_78	26.360	3488.66
step_25	19.225	4404.85	step_79	26.553	3474.37
step_26	19.281	4388.87	step_80	26.568	3435.23
step_27	19.292	4356.60	step_81	26.735	3422.01

Table 5 (continued)

Iteration	Cost	Emergy	Iteration	Cost	Emergy
step_28	19.298	4298.58	step_82	26.775	3420.01
step_29	19.492	4284.28	step_83	26.902	3412.52
step_30	19.507	4245.15	step_84	26.958	3396.55
step_31	19.674	4231.92	step_85	26.968	3364.27
step_32	19.714	4229.93	step_86	27.146	3354.18
step_33	19.841	4222.44	step_87	27.312	3348.58
step_34	19.896	4206.47	step_88	27.386	3320.53
step_35	19.907	4174.19	step_89	27.730	3304.83
step_36	20.085	4164.09	step_90	28.078	3296.03
step_37	20.192	4161.17	step_91	28.244	3290.43
step_38	20.325	4130.44	step_92	28.318	3262.38
step_39	20.405	4127.36	step_93	28.662	3246.68
step_40	20.571	4114.14	step_94	29.315	3245.88
step_41	20.611	4112.14	step_95	31.460	3237.61
step_42	20.738	4104.65	step_96	31.500	3235.61
step_43	20.794	4088.68	step_97	31.627	3228.12
step_44	20.804	4056.41	step_98	31.683	3212.15
step_45	20.811	3998.39	step_99	31.693	3179.87
step_46	21.005	3984.09	step_100	31.871	3169.78
step_47	21.020	3944.95	step_101	32.037	3164.18
step_48	21.187	3931.73	step_102	32.111	3136.13
step_49	21.226	3929.74	step_103	32.455	3120.43
step_50	21.353	3922.25	step_104	32.803	3111.63
step_51	21.409	3906.27	step_105	32.969	3106.03
step_52	21.420	3874.00	step_106	33.043	3077.98
step_53	21.597	3863.90	step_107	33.387	3062.28
step_54	21.705	3860.98	step_108	34.040	3061.48

We generated 108 efficient solutions. Note that the last efficient point with the cost value of $34.040 and emergy value of 3061.48 kcal is the minimum emergy solution.

As we have all of the efficient solutions, the frontier curve is drawn, and given in Figure 7.

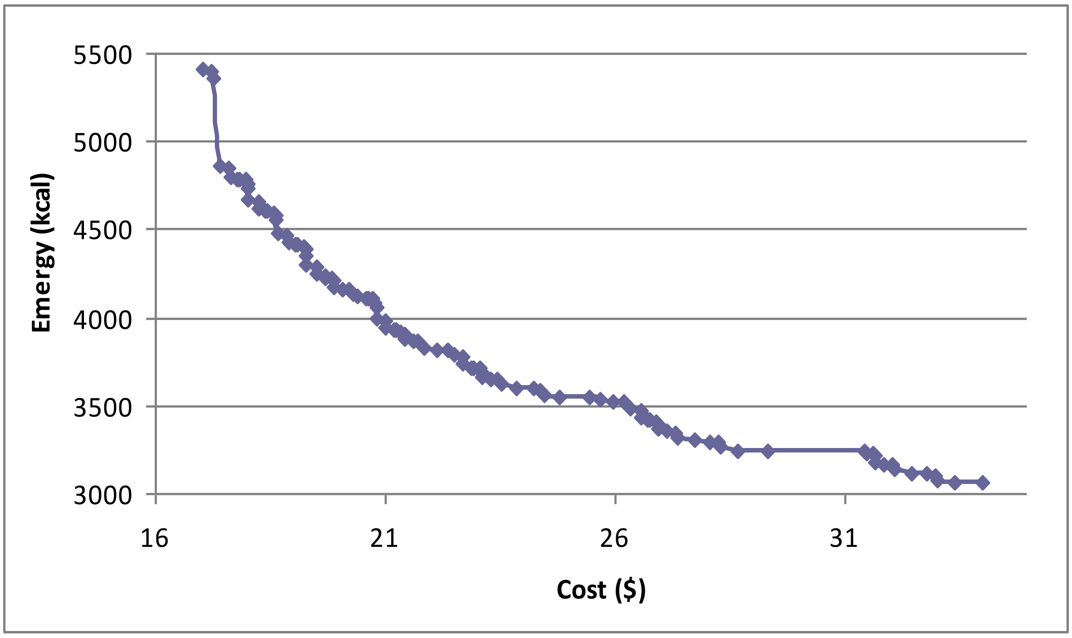

Figure 7 Frontier Curve for Discrete Solutions of CE1

Since we have many solutions, the frontier curve is very accurate. As it was mentioned in Chapter 3, the frontier curve in the linear model is the approximate efficient frontier. The following graph compares these two models.

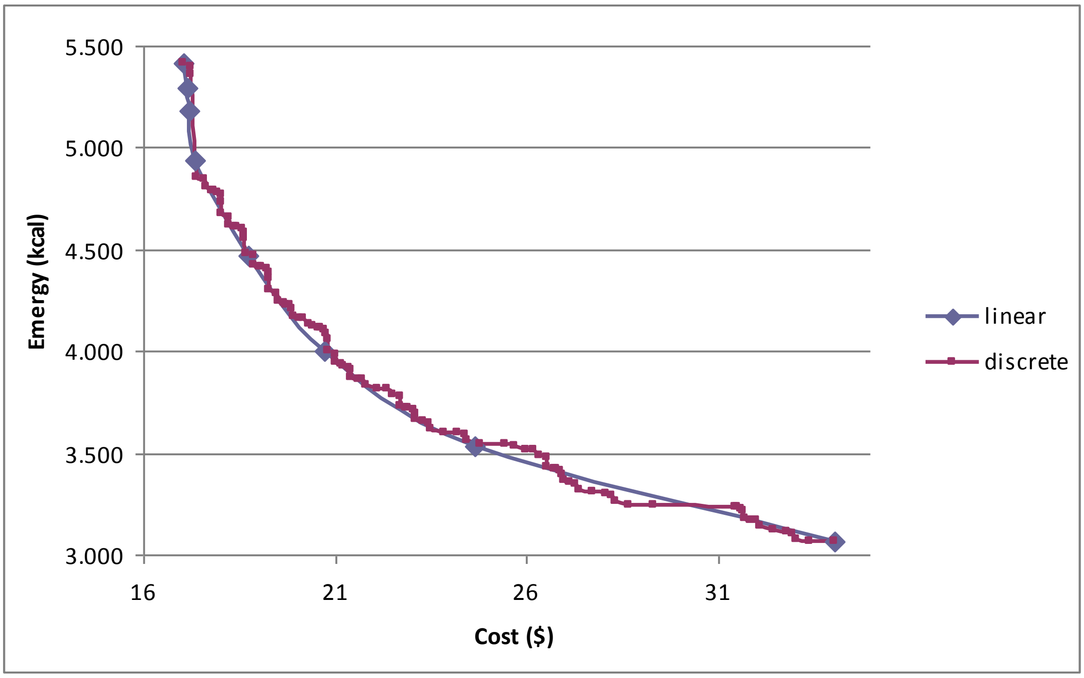

Figure 8 Linear vs. Discrete Solutions of CE1

We compare the discrete and linear models in computational effort, and report our findings in Table 5.

Table 5 Computational Efforts of Linear and Discrete Models

Criterion	Linear	Discrete
# of solutions	8	108
Computation time per solution	< 1 sec.	< 1 sec.
# of iterations	33	109
Success rate	100%	100%
Memory usage	0.7 Mb	1.4 Mb

For the linear model, we generated only 8 solutions, where as the ECM generated 108 solution for the discrete model. Since the model is relatively small, the 108 points corresponding to the efficient solutions is a reasonable number. However, for large models, the number of efficient solutions, or the effort of running the model, is expected to increase. For instance, CE2 has 40 activities and the corresponding ECM solution generates 935 efficient solutions.

The Other Examples

Four more examples are studied in this fashion. Their data figures, solution sets and frontier graphs are documented in Appendix B.

CE2 and CE3 are generated to observe effect of sub-assembly structures. CE2 has 40 activities and each activity has random number of modes between 2 and 4. The first 39 activities have sub-assembly merge type relationship. CE3 has 16 activities and each activity has random number of modes between 2 and 6. All activities, beside the last three, have sequential (serial) type relationship.

For CE2, the GAMS solution process ends up with 935 efficient solutions for discrete trade-off model, where as, CE3 has only 48 efficient solutions for the discrete trade-off model. The ECM is found to be robust enough that both examples considered were successfully solved by GAMS in a few seconds. However, as it is expected, the computation time for CE2 reached a couple of minutes, (126512 iterations at maximum), whereas solutions of CE3 were always obtained in less then a second.

For the activities that have more then two modes, sub-assembly merge type relationships generate more alternatives than those by sub-assembly alternate relationships. To test this, CE4 is solved once while all sub-assembly activities on its network were merge type. And they were changed to alternate type and solved again.

As it is expected, the CE4 discrete model has 38 efficient solutions when it has sub-assembly merge type relationship and only 4 solutions when it has sub-assembly alternate type relationship.

To test the limits of the model, CE5 which has 148 activities is generated. The model is solved in couple of minutes for single efficient solution. For an estimated 1000 efficient solutions, the computational difficulty of obtaining the frontier curve is estimated to be few tens of hours.

CHAPTER 5

TIME/EMERGY/COST TRADE-OFF MODELS

The models we studied so far consider the trade-offs between monetary cost and emergy but ignore the time component. However, there may be some cases where time is also important. Consider our lahmacun example. For the transportation activity, the railway option seems not only cheaper than road transportation but also consumes less energy and produces less CO_2. Nevertheless, in reality, railway is not one of the popular transportation options for industry, due to its time. In food industries, in particular for perishable products, quick transportation is essential.

5.1. Time/Emergy/Cost Trade-Off Models

It is possible to assign a monetary value to time. In the project management discipline, there are predefined benefits for early completion or explicit punishments for tardiness. However, for the general case, it is very hard to measure the penalty for lateness or lost sales. Therefore, as in our previous models, we will generate meaningful efficient solutions and leave the final decision to the decision maker.

Variables

In addition to the variables of the models in parts 3.2 and 3.3, the following decision variables are introduced.

S_{ij} = starting time of activity i-j

If we configure the network such that activity 0 is the starting node and activity n+1 is the terminal node, S_0 is starting time of entire network, where as S_{n+1} is its completion time.

Parameters

The following additional parameters are introduced.

t_{ijm}= process time of activity i-j in mode m.

T_{min} = minimum possible time that the project could end, i.e., deadline of the project.

Constraints

Constraint (9) ensures that the project completes no later than its deadline, T.

$$S_{n+1} \leq T \qquad (9)$$

Each activity has one successor and could have number of precessor.

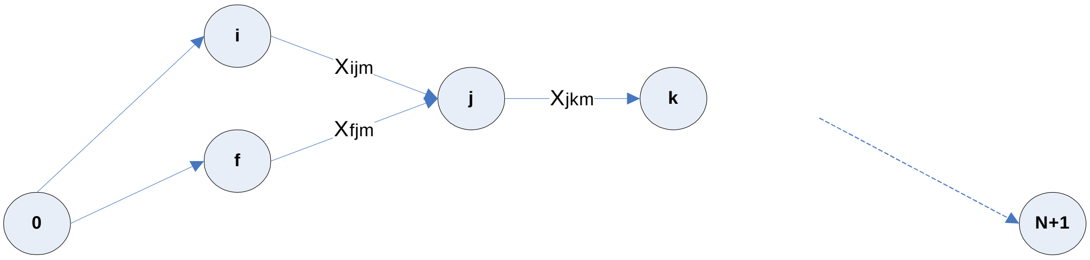

Figure 9 Precedence Relationship

$$\mathrm{S}_{\mathrm{ij}} = \mathrm{S}_0$$ *For all (i-j) with no predecessor* (10)

$$\mathrm{S}_{\mathrm{jk}} \geq \mathrm{S}_{\mathrm{ij}} + \sum_m \mathrm{Y}_{\mathrm{ijm}} * \mathrm{t}_{\mathrm{ijm}}$$ *For all (j-k) and (i-j) such that (i-j) precedes (j-k)* (10)

Objective Function

Now we have three objective functions, one for cost, emergy and time.

$$\mathrm{f}_1(\mathrm{x}) = \sum_i \sum_j \sum_m (c^m{}_{ijm} * X_{ijm})$$

$$\mathrm{f}_2(\mathrm{x}) = \sum_i \sum_j \sum_m (c^e{}_{ijm} * X_{ijm})$$

$$\mathrm{f}_3(\mathrm{x}) = \mathrm{S}_{\mathrm{n}+1}$$

Similar to the previous models, we apply the ECM. While minimizing cost, we set limits on the emergy and time values.

$$\min \sum_i \sum_j \sum_m X_{ijm} * c^m_{ijm}$$

Solution

To generate the efficient solution set, we need the minimum and the maximum possible ending times for the entire project. These two values will be used as bounds.

To find maximum possible completion time, we solve the following LP by setting all activities to their longest time modes.

min S_{n+1}

s.t. Precedence constraints (10)

All variables ≥ 0

(1)

Similarly, to find minimum completion time via the above linear program, we set all activity modes to their smallest times. Alternatively, we could use the Critical Path Method to find the minimum and the maximum possible completion times.

Once, the upper and lower bounds are found, the efficient solution set is generated by following algorithm. This algorithm is the adaptation of ECM to our model.

Step 1: Find the minimum time (T_{min}) by setting all task times to the minimum values.

Step 2: Set the deadline constraint ($\mathrm{S}_{n+1} \leq \mathrm{T} = \mathrm{T}_{\min}$)

Step 3: Find the minimum cost and corresponding emergy value (c_1* and E_1*)

Step 4: Limit energy usage ($\sum_{i} \sum_{j} \sum_{m} X_{ijm} * c^{e}_{ijm} \leq E_1^{*} - \varepsilon$) and find a new pair (c_2* and E_2*)

Step 5: Update the emergy constraint (E_1* = E_2*) till it gets infeasible

Step 6: Update deadline constraint ($\mathrm{T} = \mathrm{T} + 1$) till $\mathrm{T} = \mathrm{T}_{\max}$

It is possible to have many solutions with identical cost and emergy values but different S_{n+1} values. In order to obtain the smallest T value among those solutions, hence obtain an efficient point, we modify the objective function value as follows.

$$\min \sum_{i} \sum_{j} \sum_{m} X_{ijm} * c_{ijm}^{m} + \delta * S_{n+1} \qquad (11)$$

where δ is a small coefficient. The above function breaks the ties, if any, in favor of the smallest S_{n+1} value. The magnitude of δ is important, however, as it may cause to skip some efficient solutions.

CHAPTER 6

COMPUTATIONAL EXPERIENCE WITH TIME/EMERGY/COST TRADE-OFF MODELS

The five examples discussed in Chapter 4 are re-examined by including the time as another criterion. The time values for the activities are assumed to be discrete integers. As cost and emergy, the activity times are generated by the Excel random generator function. In this chapter, we discuss the first example (CE1) in detail. The results of the other four examples are reported in Appendix B.

It is also possible to perform mode elimination in the time/cost/emergy case. Similarly, a mode m_1 dominates m_2 if and only if they belong to same activity and each cost index and time figure for m_1 is better than those for m_2**.** For the timed version of CE1, 14 out of 59 modes can be eliminated. These eliminated modes are shown in Table 6.

Table 6 Eliminated Modes in CE1 for Time/Emergy /Cost Trade-off Model

Activity	Mode	Activity	Mode
1-2	c	12-13	d
6-2	a	13-14	c
3-4	a	13-14	d
8-9	b	15-19	a
9-10	c	16-17	c
10-11	c	18-19	a
11-19	d	19-20	a

6.1. Time/Emergy/Cost Trade-Off Solutions

As it is mentioned in Chapter 5, the solution process starts with finding upper and lower bounds for time. All activities are assigned to their maximum value. And the Critical Path Method (CPM) method is applied. This gives the longest path from the source node to the sink node. For CE1, the longest path is found to be 95. Then, the maximum project length cannot exceed **95** time units.

Similarly, all activities are assigned to their minimum value and the minimum time is calculated as **41** time units, which is taken as the lower bound.

It is clear that the completion time of any efficient solution must be between 41 and 95. For the next step, we set the time value as the minimum of 41 and generate efficient solutions as before, using ECM. Table 6 demonstrates the solution set generated for T =41.

Table 7 Efficient Solutions for $S_{n+1} \leq 41$

Time	Cost	Energy	Time	Cost	Energy
41	26.372	6824.31	41	28.185	6632.68
41	26.561	6810.36	41	29.545	6627.41
41	26.576	6772.15	41	29.599	6611.82
41	26.738	6759.24	41	29.61	6580.31
41	26.901	6749.98	41	30.018	6537.61
41	26.956	6734.39	41	30.862	6525.84
41	26.966	6702.89	41	31.27	6483.13
41	27.374	6660.18			

This set contains all efficient points for T =41. Similarly, it is possible to generate all efficient solutions for any 41≤ T ≤ 95 in this way. In essence, we add a constraint that limits the total activity time, or deadline. This process may be viewed as an extension of ECM to include another criterion. However, in real-life applications, the computational effort required to obtain the efficient points for all deadlines may not be justifiable. Instead, it may be sufficient to pick a subset of the deadlines and compute the solutions only for these time values. If deemed useful by the decision maker, further values of deadlines may be added to the subset later. We set upper bound on deadlines (and create efficient solutions with constraints T ≤ 41, 50, 55, 60, 70 and 95.

The solution sets of CE1 for those deadlines are presented in Appendix B.

Table 8 presents the minimum cost, the minimum energy solutions and number of solutions found for each deadline.

Table 8 Solutions of CE1 for Different T Values

	Minimum Cost Solution		Minimum Emergy Solution		Number of Solutions
Time	Cost	Emergy	Cost	Emergy	
41	26.372	6824.31	31.270	6483.13	15
50	18.784	6242.32	28.373	4694.68	55
55	17.809	5830.21	26.371	4234.36	55
60	17.521	5510.80	29.234	3760.71	70
70	17.046	5412.83	29.498	3395.44	88
95	17.046	5412.83	34.040	3061.48	108

As a first observation, as the deadline constraints relaxes, we get more solution and their cost and emergy values are better.

As we have all solutions for the selected deadlines, we can create Pareto Front curves. They can be seen in Figure10.

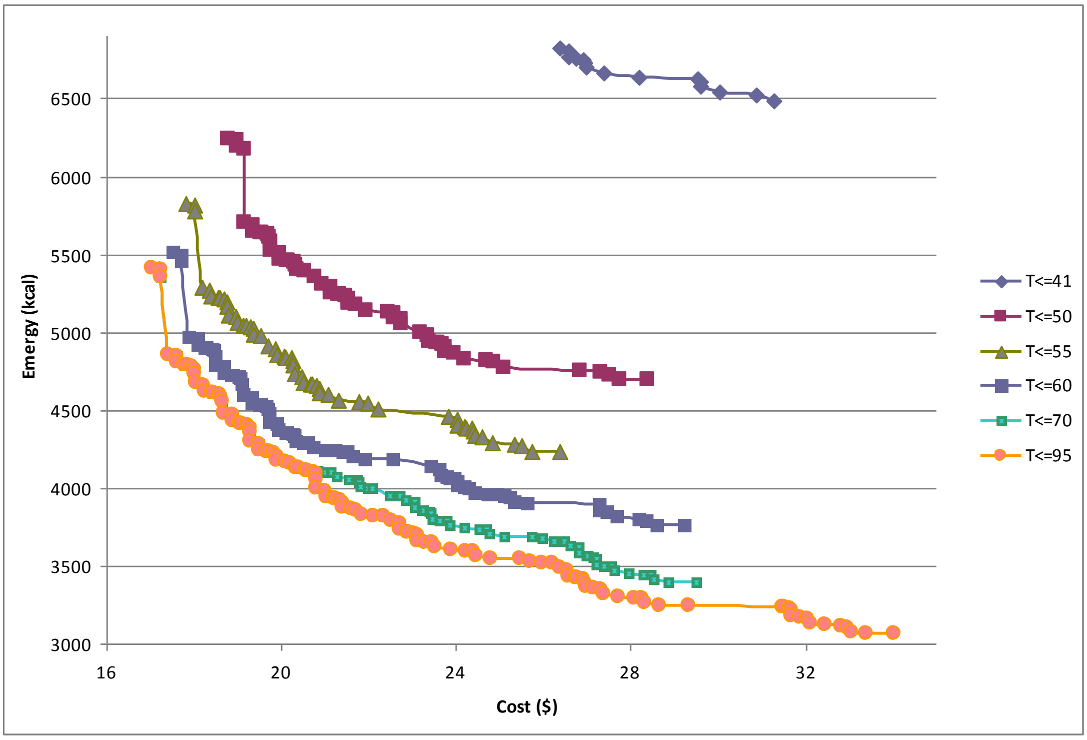

Figure 10 Frontier Curves for Different Deadlines

As observed, as we have longer activity completion times, the problem is relaxed, and hence , we obtain better solutions for cost and emergy. This behavior is fully expected. It further validates our approach, model and solution technique.

Second, it is obvious that after a certain point, relaxing deadline constraint has no positive impact for the cost or emergy figures. For instance, for the deadline of T≤95, time values are no more than 72 time units. If we were to iterate the ECM with T≤94, T≤93, ..., for instance, we would be obtaining the same solution as T≤72.

This is further motivation to, at least initially, consider a subset of the deadlines in the solution process.

The same observations hold for the solutions to the other examples, CE2 to CE4. It is clear that cost and emergy values never get worse as deadline constraint relaxes.

For most of the cases, the number of points on the frontier tends to increase as deadline constraint relaxes. However, this is not necessarily so. For instance, in CE3, we have 27 efficient points for $T \leq 40$ whereas, $T \leq 50$ has only 20 efficient points.

In general, the frontier curves are well-behaved, displaying a family of curves that seem to provide enough insights to a decision maker. Moreover, as mentioned, if need be, intermediate values may be obtained by simply performing another iteration of the solution procedure with a given deadline.

CHAPTER 7

CONCLUSIONS AND FURTHER REFINEMENTS

7.1. Conclusions

Sustainability has become a buzzword in recent months. The topic has gained media attention, especially after the global financial crisis of Fall 2008. There is much talk in the media about a new world economic order. If so, one may ask, how will all this affect industry, and industrial engineering? Reflection on the issue seems to indicate that to make operations or products more "sustainable" one must pay due attention to natural resources. The resources must be maintained by adequate operations that guarantee appropriate levels of "renewability." It is apparent that many of such resources were hitherto assumed to be infinite and without cost. Recent science on climate change by international groups, such as the United Nations and the International Panel on Climate Change, indicates that the most immediate danger is from global warming, caused by the use of fossil fuels. The energy considerations of most industrial production fails to capture the true cost of energy. Energy, embodied in a product, or emergy, may thus be promoted to a level at par with other costs in making management decisions. This seems to be a first-order modification to decision making in the era of "sustainable industry."

The work in this thesis is an initial attempt to modify decision making in such an era. We first consider cost and emergy, as the two components of a "generalized cost vector." We then enlarge our scope to include time. Time, as a criterion, has a qualitatively different effect on the decision making models. This is partly due to the precedence relations among the various activities. In addition, time is trade-able throughout the project. That is, one may use the time saved in any epoch at any other phase of the product. In contrast, the cost of an operation is usually either independent of other costs, or dependent only on the previous or next operations.

The thesis contributes to the current literature by providing three models, namely the linear and discrete emergy/cost trade-off models, and the time/emergy/cost trade-off model. The models are robust enough to be solved by standard solution packages. We used GAMS, and found the computation times to be in seconds. Moreover, the problems we face are scalable. That is, even if we have complicated products that are described by large activity networks, we can always partition the product and activities into its major sub-activities and sub-products. In some sense, there seems to be an appropriate level of modeling a product in this way. There is little incentive to model a product with thousands of activities. A collection of a few tens of activities seem appropriate. These result in models that are handled by GAMS in a few seconds.

The models developed are also good initial constructs upon which other aspects may be modeled. Some of these possible extensions were described in the previous section.

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APPENDIX A

LAHMACUN

Table A.1 Full Ingredient List for Lahmacun

Ingredient	Amount
Dry yeast	¾ tsp
Flour	¼ cup (or more)
Salt	¼ tsp
Water	As much as it gets
Minced Meat	50 gr.
Tomato	1 (finely chopped)
Onion	1 (finely chopped)
Garlic (optional)	1 oz (minced)

A.1. Alternative Modes for Lahmacun Activities and their Emergy

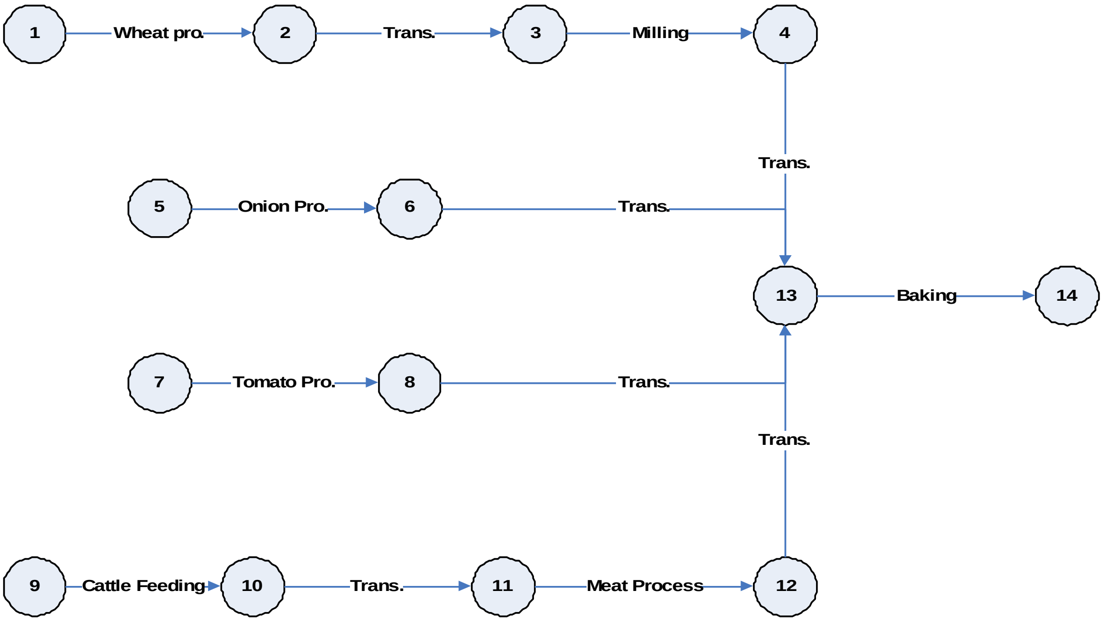

Figure A.1 Activity Network of Lahmacun

After having simple lahmacun model, the data collection stage can be started. Each activity is analyzed for its all possible and feasible modes. There could be some possible modes for some activities. However, they are not analyzed as not logical, for instance air transportation for vegetables. Some activities like transportation can be investigated together, where as methodologies for others are completely different.

Furthermore, most of the activities in Lahmacun path vary according to place the activity carried out. In other words, this study presents the way of making lahmacun in Ankara. Although, in some parts data is transferred from overseas studies, local figures is tried to be used as much as they are available.

Activity 1-2 Wheat Production

Wheat Production is a huge activity and has range variety of production types. Couple of decades ago, industrialization in agriculture was not that common. Most of production, especially for developing countries, had been relaying on animal and human force. Therefore, it is possible to generate two modes based on this difference. Also, another important issue in agriculture is organic way. The word organic here refers to type of agriculture that does not use artificial fertilizers and genetically modified seeds. Consequently, there are three options for wheat production, non-mechanized, organic and non-organic agriculture.

Since wheat production is carried out in large amounts (in tons) and in wide range of time (in months), it is difficult to calculate energy and cost figures for one kg wheat. In stead, the deduction method will be carried out.

Non-Mechanized Wheat Production

It is very hard to find non-mechanized agriculture; not even in developing countries, and investigate it to calculate cost and energy figures. Therefore, it is assumed that Turkish agriculture in 1975 would be very close. The reason to choose that year was it was the oldest year for which data was available. The table below is from Energy input-output analysis in Turkish agriculture, Ozkan et al. 2004.

Table A.2 Energy Needs for Wheat Production

Years	Human Avg. Annual Work (10^15 J)	Animal Avg. Annual Work (10^15 J)	Tractor Man. & Rep. Energy (10^15 J)	Electricity (10^15 J)	Petroleum (10^15 J)	Total Physical Energy Input (10^15 J)
1975	45.2	34.0	1.4	3.2	47.3	131.1
1980	42.9	36.9	1.5	7.8	84.9	174.0
1985	46.8	28.6	1.6	13.4	113.6	204.0
1990	48.3	25.4	1.6	24.7	134.8	234.8
1995	33.2	25.0	1.6	65.0	151.2	276.0
2000	27.4	21.9	1.6	104.0	183.3	338.2

As it can be seen, they include noticeable amount of mechanical energy. However, it is best data available. In this study, the agriculture is examined as single process. Therefore, we need how much wheat production takes place in this process. According to data of Statistical Yearbook of Turkey published by the State Institute of Statistics (SIS) under the Prime Ministry of the Republic of Turkey, Turkish cereal production was 22.2 M tons, which is 69% of gross production. It is assumed that same percent of energy was used for cereal production. Consequently, requirement per kg wheat is **447.3** kcal

Organic Wheat Production

As it is stated above, organic production here does not cover all book meaning. Simply, it means wheat production that does not employ genetically modified seeds and artificial fertilizers. Barry Ryan and Douglas G. Tiffany have worked on Minnesota’s energy consumption on agriculture in 1998. The cost and energy figures in this mode will be based on this study. The types of energies that is used in wheat production and their consumption rates are given in Table A.3.

Table A.3 Energy Needs for Wheat Production

Amount	Type
7.2 gallon/ acre	fuel-oil
0.9 gallon/ acre	gasoline
0.8 gallon/ acre	LP
30 kWh	electricity

Edward W. Allen demonstrated that wheat productivity is 42.6 bushel/acre in 1998 for US in his work on *Record U.S. Wheat Yield, Large Stocks Pressure Prices* at USDA. Consequently it is calculated that energy requirement is **401.8** kcal/kg wheat.

Winter Wheat Production

Pimentel et al. (2002) found the following distribution of energy use for both potato and winter wheat production in America. The American work is in calories and has been converted to joules (1 calorie = 4.184 joules). Table A.4 shows brief of this study.

Table A.4 Energy Inputs for Winter Wheat Production in US

Energy Item		**Quantity/ha**	**Intensity MJ/ha**
Petrol	(liter)	26.2	1.473
Diesel	(liter)	46.3	2.364
Total Fuel			3.837
Electricity	(kWhr)	13.3	172
Nitrogen	(kg)	67.3	5.322
Phosphorus	(kg)	25.8	586
Potassium	(kg)	7.0	29
Total Fertilizers			5.937
Seed	(kg)	104.3	912
Insecticides	(kg)	0.3	21
Herbicides	(kg)	1.7	1.674
Total Agrichemicals			1.695
Transportation	(kg)	182.6	515
Machinery	(kg)	19.0	3.347
Total			**16.414**

Then using the yield productivity rate that Edward W. Allen (1998) established, it is calculated that energy input for winter wheat production is **3.447** MJ/kg wheat.

Activity 2-3 Wheat Transportation

For all transportation activities, there exist two meaningful and feasible alternatives; road transportation and railway transportation. Also, it is assumed that there is linear constant cost multiplier for every unit distance. The energy requirement for transportation by truck is estimated **1.2** kcal/kg/km (Pimentel et al., 2007). This estimate is based on the fact that trucks diesel fuel consumption is about 0.143 l per 1 km (Thor and Kirendall, 1982).

On the other hand, moving goods by railway transportation requires **0.32** kcal/kg/km which is almost one forth of truck transport. The other two transportation ways, barge and airway transportation covers two extreme sides. Energy input in barge transport is about 0.1 kcal/kg/km where as it is 6.36 kcal/kg/km in air transport.

As it is stated before, only road and railway transportation alternatives will be taken into account. All distance data is exported from Turkish General Directorate of Highways for roadway distance and from Turkish State Railways statistics.

Road Transportation

Since the constant is known, all we have to do is to estimate distance between wheat production land and mills. For Turkey, large amount of wheat production is carried out in Konya region. For wheat milling activity, there is no such dominant city but most of flours that are randomly selected in Lahmacun restaurants is came from Konya. The road distance between Konya and Adana is 356 km, which concludes 472.2 kcal/kg.

Railway Transportation

Similarly, the railway distance between Konya and Adana is 370 km. Then, energy input for railway alternative is **118.4** kcal/kg.

Activity 3-4 Milling

Diesel Mills

Mohammed Shu’aibu Abubakar and Bobboi Umar conducted a study on the evaluation of energy use patterns in two flour mills; Maiduguri and Yobe. For Yobe Flour Mills, manual energy consumed accounted for 0.1%, electrical energy accounted for 7% while diesel fuel consumed accounted for 92.9% of the total energy inputs over the years under review. Maiduguri Flour Mills, manual energy accounted for 0.1% while diesel fuel energy consumed accounted for 99.9%. Manufacture, Transport and Repair (MTR) energy was not evaluated due to insufficient data on the masses of machines available in the industries and on their usage.

Yobe Flour Mills is chosen to demonstrate diesel type flour mills. Table A.5 shows energy requirements and amount of wheat processed from 1998 to 2004.

Table A.5 Energy Requirements for Diesel Wheat Mills

Year	Manpower (MJ)	Liquid Power (MJ)	Output (kg)
1998	120	191200	75000
1999	132	191200	75000
2000	120	200760	75000
2001	132	207930	75000
2002	126	207930	75000
2003	120	215100	75000
2004	144	215100	90000
Mean	128 ±8.9	204174 ± 10126.5	77143 ±5669.5

Therefore, energy needed for flour milling is **2.648** MJ/kg in diesel mills.

Electrical Mills

Table A.6 demonstrates technical specifications of electrical flour machine. (http://sjzafrica.en.alibaba.com/product/20166274550143576/6FYDT_8_Maize_Flour_Milling_Machine.html)

Table A.6 Technical Speciation of Electrical Wheat Mills

Equipment Parameter:

1. Capacity:8-10T/24h

2. Product category:

3. Consume:60-90kWh/T

4. Power:55-65kw

5. Dimension L×W×H: 16×6×4m

6. Product: corn flour: about 45%; Grits: about 35% Embryo. Germ: about 20%.

Product Parameter:

Size of corn flour: all pass through 60M sieve net, not exceed 50% keep on 80M sieve net.

Sandiness contained: not pass 0.02%

Magnetic metal contained: not pass 0.03g/kg

Moisture:storage:13.5-14.5%;edible 16-18%

Color and odor: pink, odor and taste is normal

Fat contained:2-3.5%

As it can be seen from Table 5 Energy need for electrical flour milling is 75kWh/T. According to Turkish Electricity Transmission Company Statistics, 2003; 2569 kcal/kWh is needed in hard coal electricity generators, 2628 kcal/kWh is needed in lignite electricity generators, 2189 kcal/kWh is required in natural gas electricity generators and 2408 kcal/kWh is required in diesel electricity generators. Turkish Electricity Generation Co. Inc estimated that %32 of electricity is generated by natural gas; %31 is by petroleum and 28% by lignite at year 2007. Then, it is estimated that 1 kWh electricity costs 2398.7 kcal in Turkey. Note that loss in transmission and distribution is ignored.

As a conclusion, electrical mills cost **179.9** kcal/kg.

Activity 4-13 Flour Transportation

Distance between Ankara and Adana is 490 km by road and 674 km by railways.

Road Transportation

Then it is **564** kcal for truck transportation

Railway Transportation

And **215.7** kcal/kg for railways.

Activity 5-6 Onion Production

Arable & Outdoor Onion Agriculture

In 2004, Andrew Barber’s work “Seven Case Study Farms: Total Energy & Carbon Indicators for New Zealand Arable & Outdoor Vegetable Production, 2004” concluded following table, which explains energy needs for onion production

Table A.7 Energy Needs for Onion Production

	Quantity/ha	MJ/ha	%
Field operations (l)	319	13900	27.7
Total diesel use (field op. + transport) (l)	460	20000	39.6
Total electricity use (kWh)	317	2600	1.3
Total fertilizer	-	12800	25.7
Total agrichemicals †	-	12000	24
Total capital	-	4700	9.4
Total energy	50	50100	100
Total energy (incl. packhouse/office)		52100	
Yield (tonnes)	59	104400	
Overall Energy Ratio (output: input) = 2.1			
Renewable energy (kWh)	49	400	0.8
Renewable energy (kWh)			
(incl. postharvest inputs)	200	1600	3
Carbon emissions (t CO2)	3.5		
Taxable carbon emissions (t CO2) & ($)	1.3, $33		
† Due to an extremely wet and humid season this figure is twice as large as normal			

Afterward, energy input for Arable & Outdoor Onion Production **0.499** MJ/kg.

Organic Agriculture

According to Ministry of Agriculture, Fisheries and Food, Research and Development Final Project Report, 2000 “Energy use in organic farming systems”; Onion output–input energy ratio in UK 2.41. Correspondingly, study of Andrew Barber “Seven Case Study Farms: Total Energy & Carbon Indicators for New Zealand Arable & Outdoor Vegetable Production, 2004” indicates that energy output of onion is 1760 kJ/kg. Then, energy input for Organic Onion Production **4.242** MJ/kg.

Activity 6-13 Onion Transportation

Onion is kind of local product. Its agriculture is suitable for most of climate in Turkey. Besides, Ankara is one of the top three onion producing cities. Therefore, for this activity only domestic transportation will be taken into account. Consequently, railway opportunity is eliminated.

Road Transportation

It is assumed that domestic transportation is around 50 km. Then it costs **60** kcal/kg.

Activity 7-8 Tomato Production

Greenhouse Agriculture

The table below demonstrates energy inputs in greenhouse vegetable production. It is taken from an input-output energy analysis in greenhouse vegetable production: a case study for Antalya region of Turkey, Ozkan et al, 2003.

Table A.8 Energy Needs for Greenhouse Tomato Production

Inputs	Quantity per unit area (ha)	Total energy equivalent (MJ)	%
Chemicals (kg)	98.7	9988.4	7.84
Human power (h)	3248.2	7470.9	5.87
Machinery (h)	46.3	3000.2	2.36
Nitrogen (kg)	320.0	21164.8	16.62
Phosphorus (kg)	363.0	4515.7	3.55
Potassium (kg)	293.0	3266.9	2.57

Table A.8 (continued)

Inputs	Quantity per unit area (ha)	Total energy equivalent (MJ)	%
Manure (tonnes)	68.2	20671.4	16.24
Seeds (kg)	0.1	0.1	0
Diesel-oil (l)	727.5	40965.5	32.17
Electricity (kWh)	4400.0	15840.0	12.44
Water (m3)	700.0	441.0	0.35
Total energy input (MJ)			**127324.9**
Yield (kg/ha)			**160000**

Consequently, energy needed for greenhouse type tomato production is **0.796** MJ/kg

Traditional Agriculture

Esengun et al. carried out a study to determine the input–output energy consumption and to make a cost analysis of intermediate type stake-tomato grown in open field in Tokat province of Turkey in 2006.

According to his study, the total amount of energy used for various practices in the process of stake-tomato production was calculated to be 96.957.36 MJ/ha and tomato yield is 97.000 kg/ha. As a result, energy needed for traditional type tomato production is **0.999** MJ/kg

Activity 8-13 Tomato Transportation

Location of tomato production varies on season of production. In winter, most of production is carried out in Antalya region. Interestingly, same situation exists in summer because of price effect.

Road Transportation

Distance between Antalya and Ankara is 544 km, which is 652.8 kcal/kg.

Railway Transportation

Turkish railway path doest not cover Antalya. Thus, in order to employ railways, tomato should be moved to another city Burdur by trucks and then can be carried by train. Antalya- Burdur is 122 km where as Burdur-Ankara is 1305 km. Total energy consumption yields 564 kcal/kg.

Activity 9-10 Cattle Feeding

For this part, it would be easy to separate modes based on animal types; poultry, pigs and cattle. Nevertheless, taste is extremely vital in food industry. Therefore, the modes will vary on types of feeding. Also, there exists complication because of dairy production. To handle, it is assumed that meat is gained from non-dairy cattle feeding.

A cattle feeding is complex process. Although its own literature is wide, there are a few studies on energy input analysis. In 1994, is was reported that in Europe, to produce 1 kg of broiler meat, it takes 3.1 kg of dry matter feed, where as pigs require 6.2 kg of feed and non-dairy cattle 24 kg of feed.

Conventional vs. Organic Cattle Feeding

Refsgaard et al. studied on energy input evaluations for conventional and organic meat production systems in 1997. He created an index, Scandinavian Feed Unit (SFU) which represents one kg of mixture that is used for cattle feeding. SFU is consists of fodder beats, grain and other types of animal feeds. He calculated that 4.64 MJ energy is required for 1 SFU in conventional way and 2.99 MJ is needed in organic way.

By using the previous information it can be calculated that embodied energy for 1 kg meat is 26608.7 kcal in conventional meat production and 17124.9 kcal in organic meat production.

Activity 10-11 Animal Transportation and Activity 12-13 Meat Transportation

Before evaluating embodied energy figures for these two activities, it is assumed that meat will be processed either in the city where animals have raised or in the city where meat is consumed. Instead of analyzing separately, we will merge these two activities so that the place where meat is process will be insignificant.

According to State Institute of Statistics under the Prime Ministry of the Republic of Turkey, five major meat producer cites are given in the Table A.9.

Table A.9 Five Major Cities for Turkish Meat Production

City	Total Meat Production (ton kg)	Per.
KONYA	35751.775	8.73%
İZMİR	26331.378	6.43%
BALIKESİR	22587.201	5.52%
BURSA	21405.536	5.23%
AFYON	17089.49	4.17%

Considering geographical conditions, it is assumed that most of the meat consumed in Ankara comes from three cities; Konya, Bursa and Afyon. It is also assumed that their weight is same as their production amount; 48.15%, 28.83% and 23.02%.

Road Transportation

In the light of these two assumptions, it is calculated that average total distance for road transportation is 317.2 km which is equal to **380.7 kcal.**

Railway Transportation

The same distance is accepted for railway option. Then energy spent for railway option is **118.4 kcal.**

Activity 11-12 Meat Processing

Meat processing activity can be carried out many different places; varying from small butcher shops to big integrated meat process factories. Since there are very small number of studies exists on this topic, we will use single mode for this activity. We will refer to study of Ramı´rez et al. (2006), “How much energy to process one pound of meat?”. He calculated that **685** kcal is needed to process one kg of meat.

Activity 13-14 Baking

Mainly three types of ovens are available to cook lahmacun based on their energy resource; electrical, natural gas burning and LPG burning ovens. Table A.10 shows their energy needs and corresponding caloric values.

Table A.10 Different Type of Lahmacun Ovens

Type of energy	Energy need to run oven for 1 hour	Caloric vale (kcal)
electricity	18 kW/h	49500
natural gas	2.01 m3	19216
LPG	1.54 Kg.	16170

SUMMARY

Table A.11 Summary

Activity	Mode	Emergy (kcal)	α
wheat production	non-mechanized	447.3	
	organic	401.8	
	non-organic	823.9	
wheat transportation	road	472.2	
	railway	118.4	
flour milling	diesel	633.1	0.75
	electrical	179.9	0.75
flour transportation	road	564.0	
	railway	215.7	
onion production	greenhouse	119.3	
	traditional	1013.8	
onion transportation	road	60.0	
tomato production	greenhouse	190.2	
	traditional	238.9	
tomato transportation	road	190.9	
	railway	239.8	
cattle feeding	conventional	26.608.7	
	organic	17.124.9	
animal transportation	road	472.2	
	railway	118.4	
meat processing	cumulative	685.0	
meat transportation	road	472.2	
	railway	118.4	
baking (20 min)	electrical	16500.0	
	natural gas	6405.3	
	LPG	5390.0	

A.2. Calculation Emergy for Single Lahmacun

- We need 0.05 kg flour per lahmacun. It is assumed that Turkish wheat production consumes the same emergy as non-mechanized wheat production option, which is 447.3 kcal / kg. And it is fact that wheat is transported by truck in Turkey (472.2 kcal / kg). Assume it turns into flour in diesel mills (633.1 kcal / kg) and α ratio is around 0.75. Similar to wheat, flour is transported by trucks (564 kcal / kg)

Energy spent for 0.05 kg flour is 0.05 * (447.3 + 472.2) + 0.05 * (1 / 0.75) * (631.1 + 564) = **121.2** kcal. (*61.2 kcal for transportation*)

- Onion needed per lahmacun is more or less 0.05 kg. The Turkish onion production is assumed to be traditional type (1013.8 kcal) and it is transported by road (60 kcal).

Energy spent for 0.05 kg onion is 0.05 * (1013.8 + 60) = **53.7** kcal. (*3 kcal for transportation*)

- Tomato needed per lahmacun is about 0.05 kg. The Turkish tomato production is assumed to be traditional type (238.9 kcal) and it is transported by road (190.2 kcal).

Energy spent for 0.05 kg tomato is 0.05 * (238.9 + 190.2) = **21.5** kcal. (9.5 *kcal for transportation*)

- We need about 0.05 kg minced meat per lahmacun. It is assumed that Turkish meat production more similar to conventional meat production option, which is 26608.7 kcal / kg. And it is fact that meat and animal transportation is carried out by trucks in Turkey (380.7 kcal / kg). Meat processing has one alternative (685 kcal) and scrap rates are considered in emergy study. Thus, we accept α ratio to be 1.

Energy spent for 0.05 kg meat is 0.05 * (26608.7 + 380.7 + 685 kcal) = **1383.7** kcal. (*19 kcal for transportation*)

- Assume that electrical oven (16500 kcal / h) used 20 min for one lahmacun.

Energy spent for baking is **5500** kcal.

To sum up, 7080.1 kcal is emergy value for one lahmacun.

APPENDIX B

NUMERICAL EXAMPLES

B.1. CE1

Table B.1.A Cost Emergy alpha and Time Figures for CE1

	Mode	Cost	Emergy	alpha	Time
activity 1.2	mode a	2.99	417.14	0.98	5
	mode b	0.43	528.23	0.97	14
	mode c	4.33	513.36	0.63	14
activity 2.3	mode a	3.79	651.71	0.88	17
	mode b	1.70	902.34	0.74	12
activity 6.2	mode a	0.40	453.11	0.85	10
	mode b	0.13	492.32	0.99	10
	mode c	3.87	150.42	0.60	19
	mode d	1.34	425.51	0.72	4
activity 3.4	mode a	4.64	881.10	0.80	20
	mode b	2.52	485.82	0.78	19
	mode c	4.37	644.56	0.76	18
	mode d	03.11	95.12	0.91	8
activity 7.3	mode a	1.50	427.18	1.00	20
	mode b	1.62	991.09	0.83	3
activity 4.5	mode a	0.79	901.03	0.86	12
	mode b	4.69	383.98	0.79	10
	mode c	0.99	166.04	0.83	13
activity 5.20	mode a	2.53	79.46	0.78	15
	mode b	2.73	738.28	0.94	5
activity 8.9	mode a	0.29	329.23	0.88	3
	mode b	4.68	965.68	0.86	13

Table B.1.A (continued)

	Mode	Cost	Emergy	alpha	Time
activity 9.10	mode a	433	32.99	0.62	13
	mode b	0.67	525.24	0.83	6
	mode c	4.55	959.52	0.90	12
	mode d	2.59	100.21	0.93	17
activity 10.11	mode a	2.93	741.27	0.85	2
	mode b	4.59	407.59	0.73	3
	mode c	3.45	738.14	0.78	14
activity 11.19	mode a	2.28	132.90	0.76	15
	mode b	1.22	282.20	0.84	18
	mode c	4.15	533.28	0.59	12
	mode d	4.22	760.52	0.61	17
activity 12.13	mode a	0.22	343.56	0.83	12
	mode b	4.65	26.63	0.89	12
	mode c	2.36	850.98	0.76	4
	mode d	2.77	436.99	0.85	12
activity 13.14	mode a	1.12	232.10	0.77	12
	mode b	1.86	733.74	0.71	8
	mode c	4.90	822.05	0.83	20
	mode d	4.67	585.59	0.60	12
activity 14.15	mode a	2.52	625.54	0.76	15
	mode b	4.99	104.87	0.75	19
activity 15.19	mode a	4.79	667.59	0.44	20
	mode b	0.61	108.00	0.59	12
	mode c	1.62	977.19	0.62	7
activity 16.17	mode a	0.85	747.72	0.93	12
	mode b	2.76	312.11	0.83	10
	mode c	5.00	871.91	0.74	13
activity 17.18	mode a	2.69	387.21	0.84	7
	mode b	2.06	724.08	0.97	20
	mode c	0.60	705.59	0.90	7
activity 18.19	mode a	4.75	649.85	0.83	17
	mode b	0.30	985.68	0.99	1
	mode c	1.58	466.20	0.93	8
activity 19.20	mode a	1.85	761.26	0.86	13
	mode b	1.73	549.31	0.87	6
activity 20.21	mode a	3.82	566.32	0.84	1
	mode b	3.08	375.77	0.82	11

Table B.1.B Precedence Relationships and beta Figures for CE1

Successor	Predecessor	beta	Successor	Predecessor	beta
activity 1	activity 2	-	activity 13	activity 14	-
activity 2	activity 4	0.68	activity 14	activity 15	-
activity 3			activity 16	activity 17	-
activity 4	activity 6	0.15	activity 17	activity 18	-
activity 5			activity 11	activity 19	0.36
activity 6	activity 7	-	activity 15		0.42
activity 8	activity 9	-	activity 18		0.22
activity 9	activity 10	-	activity 19	activity 20	0.45
activity 10	activity 11	-	activity 7		0.55
activity 12	activity 13	-	activity 20	-	-

B.2. CE1 Solutions

Table B.2.A $S_{n+1} \leq 50$ Solutions for CE1

Time	Cost	Energy	Time	Cost	Energy	Time	Cost	Energy
49	18.784	6242.32	49	20.353	5400.9	50	23.363	4981.83
49	18.973	6228.36	49	20.526	5391.04	50	23.378	4943.62
49	18.988	6190.16	49	20.76	5358.19	50	23.54	4930.71
49	19.151	6177.25	50	20.942	5304.88	50	23.579	4928.77
49	19.158	5700.39	50	21.132	5290.93	50	23.703	4921.45
49	19.347	5686.44	50	21.146	5252.72	50	23.758	4905.86
49	19.362	5648.23	50	21.309	5239.82	50	23.768	4874.35
49	19.524	5635.32	50	21.348	5237.87	50	23.941	4864.5
49	19.563	5633.37	50	21.472	5230.56	50	24.176	4831.65
49	19.687	5626.06	50	21.526	5214.97	50	24.678	4817.59
49	19.741	5610.47	50	21.537	5183.46	50	24.851	4807.73
49	19.752	5578.96	50	21.71	5173.6	50	25.086	4774.88
49	19.758	5522.33	50	21.944	5140.75	49	26.826	4752.24
49	19.948	5508.37	50	22.447	5126.69	49	27.328	4738.18
49	19.962	5470.17	49	22.573	5123.3	49	27.501	4728.32
49	20.125	5457.26	49	22.584	5091.8	49	27.735	4695.47
49	20.164	5455.31	49	22.757	5081.94	49	28.373	4694.68
49	20.288	5448	49	22.757	5049.09			
49	20.342	5432.41	50	23.174	4995.78			

Table B.2.B $S_{n+1} \leq 55$ Solutions for CE1

Time	Cost	Energy	Time	Cost	Energy	Time	Cost	Energy
53	17.809	5830.21	53	19.539	4979.46	54	21.79	4551.58
53	17.998	5816.25	54	19.686	4907.83	54	21.964	4541.72
53	18.013	5778.05	54	19.875	4893.88	54	22.198	4508.87
53	18.171	5288.81	54	19.889	4855.67	54	23.822	4456.05
53	18.36	5274.85	54	20.052	4842.77	54	24.011	4442.09
53	18.375	5236.65	54	20.091	4840.82	54	24.025	4403.89
53	18.537	5223.74	54	20.215	4833.51	54	24.188	4390.98
53	18.576	5221.79	54	20.269	4817.91	54	24.227	4389.03
53	18.7	5214.48	54	20.28	4786.41	54	24.351	4381.72
53	18.754	5198.89	54	20.286	4729.77	54	24.405	4366.13
53	18.765	5167.38	54	20.476	4715.81	54	24.416	4334.62
53	18.771	5110.74	54	20.49	4677.61	54	24.589	4324.77
53	18.961	5096.79	54	20.653	4664.7	54	24.824	4291.92
53	18.975	5058.58	54	20.692	4662.75	54	25.326	4277.86
53	19.138	5045.67	54	20.816	4655.44	54	25.499	4268
53	19.177	5043.73	54	20.87	4639.85	54	25.733	4235.15
53	19.301	5036.41	54	20.881	4608.34	54	26.371	4234.36
53	19.355	5020.82	54	21.054	4598.49			
53	19.366	4989.32	54	21.288	4565.64			

Table B.2.C $S_{n+1} \leq 60$ Solutions for CE1

Time	Cost	Energy	Time	Cost	Energy	Time	Cost	Energy
58	17.521	5510.8	58	19.648	4526.81	58	23.801	4070.37
58	17.71	5496.85	58	19.703	4511.22	58	23.84	4068.42
58	17.725	5458.64	58	19.713	4479.72	58	23.964	4061.11
58	17.883	4969.4	58	19.72	4423.08	58	24.019	4045.52
58	18.072	4955.45	58	19.909	4409.12	58	24.029	4014.01
58	18.087	4917.24	58	19.924	4370.92	58	24.202	4004.16
58	18.249	4904.34	58	20.086	4358.01	58	24.308	4001.3
58	18.288	4902.39	58	20.125	4356.06	58	24.437	3971.31
58	18.412	4895.08	58	20.249	4348.75	58	24.715	3958.6
58	18.467	4879.48	58	20.304	4333.16	58	24.939	3957.25
58	18.477	4847.98	58	20.314	4301.65	58	25.112	3947.39

Table B.2.C (continued)

Time	Cost	Energy	Time	Cost	Energy	Time	Cost	Energy
58	18.484	4791.34	58	20.487	4291.79	58	25.218	3944.54
58	18.673	4777.38	58	20.593	4288.94	58	25.347	3914.54
58	18.687	4739.18	58	20.722	4258.94	58	25.625	3901.83
58	18.85	4726.27	58	21	4246.23	59	27.269	3892.48
58	18.889	4724.32	58	21.224	4244.89	59	27.279	3860.97
58	19.013	4717.01	58	21.397	4235.03	59	27.453	3851.12
58	19.067	4701.42	58	21.503	4232.17	59	27.687	3818.27
58	19.078	4669.91	58	21.632	4202.18	59	28.189	3804.21
58	19.119	4601.14	58	21.91	4189.47	59	28.363	3794.35
58	19.308	4587.19	58	22.548	4188.68	59	28.597	3761.5
58	19.323	4548.98	58	23.435	4135.44	59	29.234	3760.71
58	19.486	4536.07	58	23.624	4121.48			
58	19.524	4534.13	58	23.639	4083.28			

Table B.2.D $S_{n+1} \le 70$ Solutions for CE1

Time	Cost	Energy	Time	Cost	Energy	Time	Cost	Energy
68	17.046	5412.83	68	19.674	4231.92	64	23.778	3787.17
68	17.24	5398.54	68	19.714	4229.93	68	23.85	3759.78
68	17.255	5359.4	68	19.841	4222.44	64	24.186	3744.47
68	17.416	4858.23	68	19.896	4206.47	68	24.526	3735.87
68	17.610	4843.94	68	19.907	4174.19	64	24.688	3730.41
68	17.625	4804.8	68	20.085	4164.09	68	24.76	3703.02
68	17.792	4791.58	68	20.192	4161.17	64	25.096	3687.70
68	17.832	4789.58	68	20.325	4130.44	64	25.733	3686.91
68	17.959	4782.09	68	20.610	4117.42	62	25.963	3674.43
68	18.015	4766.12	68	20.839	4116.04	62	26.242	3661.72
68	18.025	4733.84	68	21.017	4105.94	62	26.465	3660.37
68	18.032	4675.82	68	21.125	4103.02	68	26.613	3632.44
68	18.226	4661.53	68	21.257	4072.29	68	26.802	3618.49
68	18.241	4622.39	68	21.542	4059.27	68	26.817	3580.28
68	18.407	4609.17	68	21.726	4055.7	68	26.979	3567.38
68	18.447	4607.17	62	21.78	4040.11	68	27.018	3565.43
68	18.574	4599.68	62	21.791	4008.61	68	27.142	3558.12

Table B.2.D (continued)

Time	Cost	Energy	Time	Cost	Energy	Time	Cost	Energy
68	18.63	4583.71	62	21.964	3998.75	68	27.197	3542.52
68	18.641	4551.44	62	22.069	3995.89	68	27.207	3511.02
68	18.683	4480.99	62	22.477	3953.19	68	27.38	3501.16
68	18.877	4466.69	62	22.701	3951.84	64	27.543	3495.7
68	18.892	4427.55	62	22.848	3923.92	68	27.615	3468.31
68	19.058	4414.33	62	23.038	3909.96	64	27.951	3452.99
68	19.098	4412.34	68	23.052	3871.76	68	28.29	3444.4
68	19.225	4404.85	68	23.215	3858.85	64	28.453	3438.93
68	19.281	4388.87	68	23.254	3856.9	68	28.525	3411.55
68	19.292	4356.6	68	23.378	3849.59	64	28.861	3396.23
68	19.298	4298.58	68	23.432	3834.00	64	29.498	3395.44
68	19.492	4284.28	68	23.443	3802.49			
68	19.507	4245.15	68	23.616	3792.63			

Table B.2.E $S_{n+1} \leq 95$ Solutions for CE1

Time	Cost	Emergy	Time	Cost	Emergy	Time	Cost	Emergy
68	17.046	5412.83	68	20.192	4161.17	72	24.806	3545.27
68	17.240	5398.54	68	20.325	4130.44	72	25.459	3544.46
68	17.255	5359.40	72	20.405	4127.36	72	25.694	3531.67
68	17.416	4858.23	72	20.571	4114.14	72	25.979	3518.65
68	17.610	4843.94	72	20.611	4112.14	72	26.208	3517.27
68	17.625	4804.80	72	20.738	4104.65	72	26.360	3488.66
68	17.792	4791.58	72	20.794	4088.68	72	26.553	3474.37
68	17.832	4789.58	72	20.804	4056.41	72	26.568	3435.23
68	17.959	4782.09	72	20.811	3998.39	72	26.735	3422.01
68	18.015	4766.12	72	21.005	3984.09	72	26.775	3420.01
68	18.025	4733.84	72	21.020	3944.95	72	26.902	3412.52
68	18.032	4675.82	72	21.187	3931.73	72	26.958	3396.55
68	18.226	4661.53	72	21.226	3929.74	72	26.968	3364.27
68	18.241	4622.39	72	21.353	3922.25	72	27.146	3354.18
68	18.407	4609.17	72	21.409	3906.27	72	27.312	3348.58
68	18.447	4607.17	72	21.420	3874.00	72	27.386	3320.53
68	18.574	4599.68	72	21.597	3863.90	72	27.730	3304.83
68	18.630	4583.71	72	21.705	3860.98	72	28.078	3296.03

Table B.2.E (continued)

Time	Cost	Emergy	Time	Cost	Emergy	Time	Cost	Emergy
68	18.641	4551.44	72	21.838	3830.25	72	28.244	3290.43
68	18.683	4480.99	72	22.123	3817.23	72	28.318	3262.38
68	18.877	4466.69	72	22.352	3815.85	72	28.662	3246.68
68	18.892	4427.55	72	22.503	3787.24	72	29.315	3245.88
68	19.058	4414.33	72	22.697	3772.95	72	31.460	3237.61
68	19.098	4412.34	72	22.712	3733.81	72	31.500	3235.61
68	19.225	4404.85	72	22.879	3720.59	72	31.627	3228.12
68	19.281	4388.87	72	22.919	3718.59	72	31.683	3212.15
68	19.292	4356.60	72	23.046	3711.10	72	31.693	3179.87
68	19.298	4298.58	72	23.101	3695.13	72	31.871	3169.78
68	19.492	4284.28	72	23.112	3662.86	72	32.037	3164.18
68	19.507	4245.15	72	23.290	3652.76	72	32.111	3136.13
68	19.674	4231.92	72	23.456	3647.16	72	32.455	3120.43
68	19.714	4229.93	72	23.530	3619.11	72	32.803	3111.63
68	19.841	4222.44	72	23.874	3603.42	72	32.969	3106.03
68	19.896	4206.47	72	24.222	3594.61	72	33.043	3077.98
68	19.907	4174.19	72	24.388	3589.01	72	33.387	3062.28
68	20.085	4164.09	72	24.462	3560.96	72	34.040	3061.48

B.2.1 CE2

Table B.2.A Cost Emergy alpha and Time Figures for CE2

		Cost	Emergy	alpha	Time
activity_1-28	mode a	4.19	356.15	0.92	3
	mode b	3.04	609.09	0.85	17
activity_2-28	mode a	3.35	863.3	0.72	15
	mode b	0.43	Şub.32	0.88	4
	mode c	3.97	601.31	0.55	6
activity_3-28	mode a	2.06	136.05	0.58	4
	mode b	4.43	23.51	0.76	5
	mode c	4.14	287.53	0.54	3
activity_4-29	mode a	4.07	397.67	0.78	7
	mode b	1.98	162.78	0.56	17
	mode c	1.05	858.58	0.56	9

Table B.2.A (continued)

		Cost	Emergy	alpha	Time
activity_5-29	mode a	0.49	663.81	0.65	12
	mode b	3.02	540.06	0.74	3
	mode c	1.85	445.88	0.97	3
activity_6-29	mode a	0.20	263.9	0.75	6
	mode b	0.79	72.62	0.65	8
	mode c	2.54	169.3	0.75	17
	mode d	1.01	551.9	0.67	19
activity_7-30	mode a	3.23	628.6	0.82	10
	mode b	1.06	315.44	0.73	11
	mode c	0.71	773.74	0.63	7
	mode d	3.11	137	0.9	7
activity_8-30	mode a	4.79	892.9	0.93	12
	mode b	3.83	525.92	0.7	1
	mode c	1.45	451.4	0.77	9
activity_9-30	mode a	4.36	85.4	0.93	18
	mode b	1.04	316.08	0.5	9
	mode c	3.75	297.45	0.67	19
activity_10-31	mode a	4.04	250.26	0.67	12
	mode b	1.91	767.93	0.56	9
	mode c	4.21	757.93	0.53	1
	mode d	4.56	795.87	0.81	14
activity_11-31	mode a	4.83	681.67	0.64	10
	mode b	1.36	667.57	0.75	4
	mode c	2.54	619.35	0.78	4
	mode d	4.85	34.82	0.93	3
activity_12-31	mode a	1.89	938.35	0.92	4
	mode b	4.18	179.19	0.61	6
	mode c	4.16	739.87	0.72	3
activity_13-32	mode a	0.35	231.05	0.87	17
	mode b	3.82	265.06	0.9	4
	mode c	1.26	317.33	0.7	9
activity_14-32	mode a	1.87	854.73	0.87	9
	mode b	3.66	201.32	0.67	7
	mode c	4.07	365.01	0.64	13
	mode d	2.08	362.6	0.57	17

Table B.2.A (continued)

		Cost	Emergy	alpha	Time
activity_15-32	mode a	3.02	213.35	0.81	3
	mode b	0.23	855.63	0.82	12
activity_16-33	mode a	4.61	978.55	0.61	14
	mode b	2.84	889.96	0.59	4
	mode c	4.18	52.86	0.8	14
activity_17-33	mode a	4.88	829.54	0.6	12
	mode b	2.09	59.94	0.82	6
	mode c	2.42	911.75	0.9	10
activity_18-33	mode a	4.09	446.68	0.82	15
	mode b	1.46	859.41	0.55	1
	mode c	3.59	84.95	0.66	18
	mode d	4.99	919.52	1	2
activity_19-34	mode a	2.82	229.95	0.66	18
	mode b	0.4	177.93	0.92	18
	mode c	1.12	34.31	0.51	20
activity_20-34	mode a	3.37	248.71	0.96	8
	mode b	4.85	247.93	0.98	10
	mode c	2.09	271.86	0.53	20
activity_21-34	mode a	2.62	688.48	0.57	16
	mode b	4.32	433.63	0.7	6
	mode c	4.07	157.31	0.72	17
activity_22-35	mode a	3.18	816.39	0.75	2
	mode b	3.11	980.14	0.91	1
	mode c	0.31	857.08	0.63	5
activity_23-35	mode a	0.59	34.15	0.93	11
	mode b	0.53	716.73	0.79	3
	mode c	0.6	628.68	0.64	15
activity_24-35	mode a	2.09	511.9	0.64	3
	mode b	2.35	113.71	0.69	12
	mode c	4.49	756.12	0.95	2
activity_25-36	mode a	0.84	724.55	0.74	2
	mode b	0.29	75	0.73	13
	mode c	2.01	844.18	0.68	4
activity_26-36	mode a	4.07	41.29	0.86	12
	mode b	3.26	76.79	0.5	19
	mode c	1.84	906.19	0.76	8

Table B.2.A (continued)

		Cost	**Emergy**	**alpha**	**Time**
activity_27-36	mode a	4.16	595.6	0.51	20
	mode b	0.99	125.72	0.77	10
	mode c	4.05	936.55	0.57	18
activity_28-37	mode a	3.87	978.24	0.56	19
	mode b	4.33	102.21	0.91	6
	mode c	3.86	88.29	0.98	7
activity_29-37	mode a	0.61	993.16	0.76	17
	mode b	3.59	928.93	0.61	7
	mode c	4.49	827.72	0.87	10
	mode d	3.57	355.53	0.66	1
activity_30-37	mode a	2.83	483.15	0.85	7
	mode b	2.93	455.05	0.59	1
activity_31-38	mode a	0.36	659.64	0.56	13
	mode b	0.55	67.22	0.84	13
	mode c	2.57	173.1	0.69	4
activity_32-38	mode a	2.27	459.34	0.68	6
	mode b	0.66	655.62	0.66	5
	mode c	4.55	898.89	0.99	16
activity_33-38	mode a	0.86	780.35	0.93	16
	mode b	0.01	555.91	0.86	13
	mode c	0.78	14.72	0.7	20
activity_34-39	mode a	1.52	737.44	0.82	4
	mode b	1.52	73.82	0.58	5
	mode c	4.08	565.25	0.81	2
activity_35-39	mode a	2.87	176.54	0.69	7
	mode b	1.08	808.26	0.99	6
	mode c	0.33	425.94	0.64	1
	mode d	3.06	276.03	0.97	2
activity_36-39	mode a	3.55	57.27	0.81	15
	mode b	3.91	204.34	0.74	14
activity_37-40	mode a	2.56	58.54	0.97	16
	mode b	1.37	817.07	0.72	14
	mode c	3.04	90.83	0.77	1
activity_38-40	mode a	1.33	828.13	0.99	15
	mode b	3.04	71.17	0.53	17

Table B.2.A (continued)

		Cost	Emergy	alpha	Time
activity_39-40	mode a	4.79	432.61	0.85	1
	mode b	1.22	885.22	0.81	12
	mode c	2.93	99.38	0.77	10
	mode d	0.96	700.14	0.74	1
activity_40-41	mode a	4.04	460.12	0.72	7
	mode b	3.81	316.21	0.73	16

B.2.2 CE2 Solutions

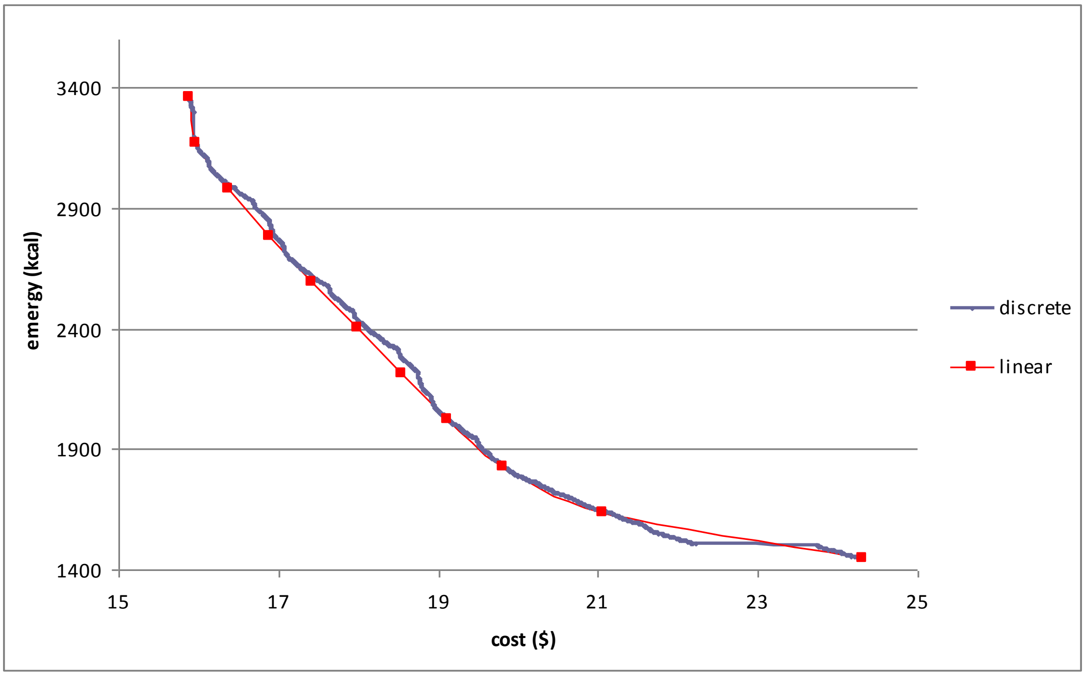

Figure B.2.A Linear and Discrete Solutions for CE2

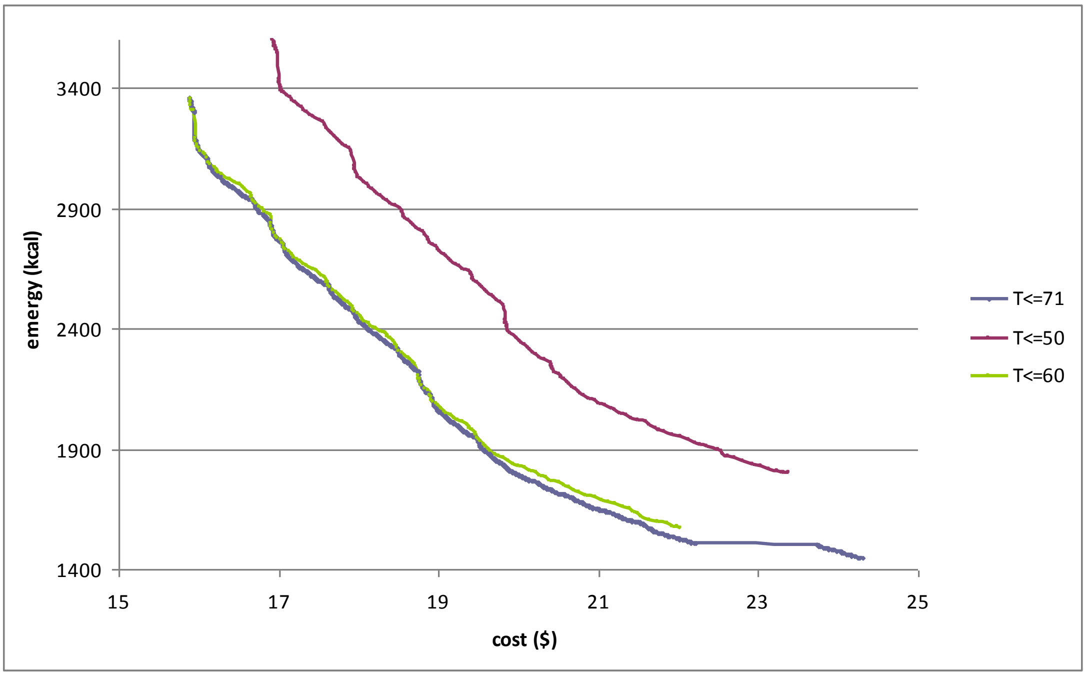

Figure B.2.B Time/Emergy/Cost Model Solutions for CE2

B.3.1 CE3

Table B.3.A Cost Emergy alpha and Time Figures for CE3

	Mode	Cost	Emergy	alpha	Time
activity_1-4	mode a	4.14	207.58	0.77	7
	mode b	0.77	644.27	0.61	14
	mode c	0.99	74.41	0.54	14
	mode d	4.09	429.76	0.62	1
	mode e	0.09	46.15	0.54	4
activity_2-5	mode a	4.08	775.32	0.64	5
	mode b	3.78	139.45	0.97	14
	mode c	1.49	540.85	0.98	1
activity_3-6	mode a	4.36	188.82	0.54	15
	mode b	3.16	40.48	0.6	18
	mode c	3.01	385.1	0.65	6
	mode d	0.58	673.01	0.67	10
	mode e	1.73	211.45	0.85	17
	mode f	4.94	417.25	0.87	9

Table B.3.A (continued)

	Mode	Cost	Emergy	alpha	Time
activity_5-8	mode a	4.36	435.48	0.69	8
	mode b	1.38	385	0.85	17
	mode c	1.86	243.04	0.78	8
	mode d	1.12	894.34	0.79	19
activity_6-9	mode a	4.83	617.79	0.87	15
	mode b	4.29	802.81	0.84	7
activity_7-10	mode a	4.17	189.73	0.7	4
	mode b	3.56	398.4	0.92	6
activity_8-11	mode a	3.03	353.46	0.64	19
	mode b	4.92	315.53	0.87	2
	mode c	2.89	122.84	0.93	12
	mode d	1.87	152.11	0.76	1
activity_9-12	mode a	1.36	975.29	0.93	4
	mode b	2.42	923.44	0.95	14
activity_10-13	mode a	0.48	669.14	0.82	5
	mode b	3.68	330.96	0.84	17
	mode c	0.11	451.11	0.91	14
activity_11-14	mode a	2.99	283.91	0.93	16
	mode b	3.26	86.48	0.74	11
	mode c	3.58	980.59	0.72	6
	mode d	1.76	24.May	0.98	8
	mode e	0.75	229.59	0.83	3
activity_12-15	mode a	1.37	507.43	0.57	6
	mode b	3.01	588.68	0.81	13
	mode c	4.57	357.87	0.84	2
	mode d	3.18	547.69	0.77	9
	mode e	0.78	793.72	0.97	15
activity_13-16	mode a	2.42	660.75	1	16
	mode b	0.93	350.82	0.67	11
	mode c	0.84	771.32	0.62	5
	mode d	4.36	656.04	0.93	13
activity_14-16	mode a	4.09	821.15	0.78	18
	mode b	0.79	342.58	0.71	4
	mode c	0.76	509.14	0.8	13

Table B.3.A (continued)

	Mode	Cost	Emergy	alpha
activity_15-16	mode a	3.81	308.88	0.79
	mode b	0.49	561.9	0.61
	mode c	1.12	562.12	0.85
	mode d	0.15	363.61	0.88
	mode e	4.56	597.19	0.74
activity_16-17	mode a	3.66	797.54	1
	mode b	3.84	134.41	0.82

Table B.3.B Precedence Relationship and beta Figures for CE3

Successor	Predecessor	beta
activity 1_4	activity 4_7	-
activity 2_5	activity 5_8	-
activity 3_6	activity 6_9	-
activity 4_7	activity 7_10	-
activity 5_8	activity 8_11	-
activity 6_9	activity 9_12	-
activity 7_10	activity 10_13	-
activity 8_11	activity 11_14	-
activity 9_12	activity 12_15	-
activity 10_13	activity 13_16	-
activity 11_14	activity 14_16	-
activity 12_15	activity 15_16	-
activity 13_16	activity 16_17	0.36
activity 14_16	activity 16_17	0.48
activity 15_16	activity 16_17	0.16
activity 16_17	-	-

B.3.2 CE3 Solutions

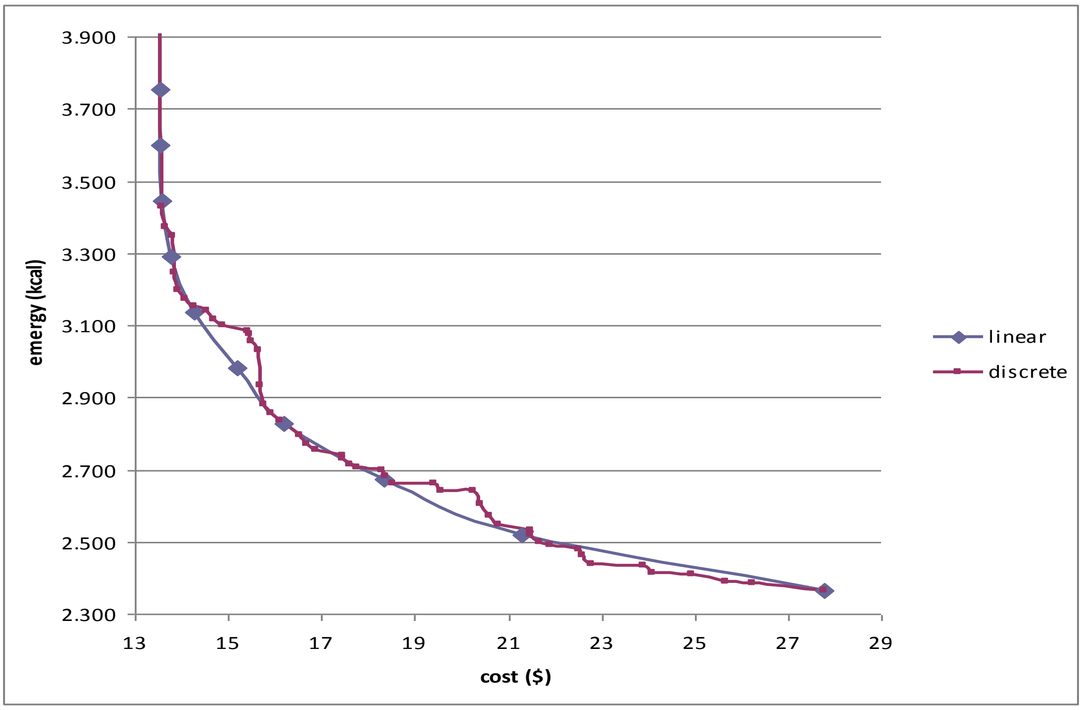

Figure B.3.A Linear and Discrete Solutions for CE3

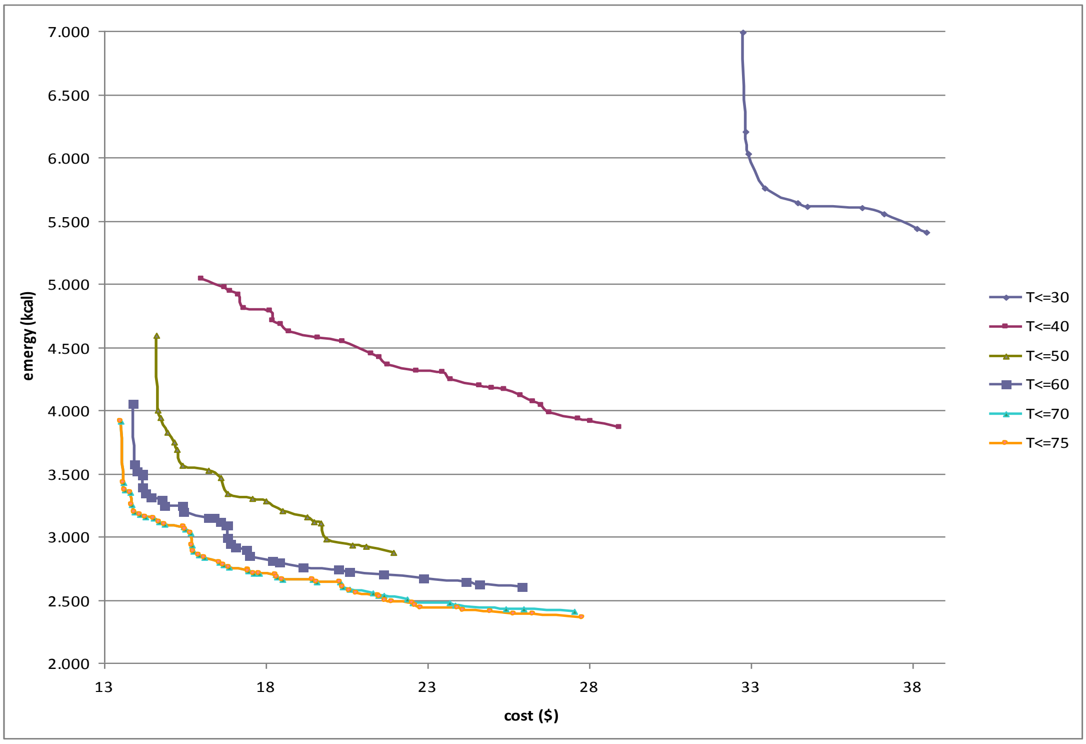

Figure B.3.B Time/Emergy/Cost Solutions for CE3

B.4.1 CE4

Table B.4.A Cost Emergy alpha and Time Figures for CE4

	Mode	Cost	Emergy	alpha	Time
activity 1_8	mode a	3.7	819.75	1	4
	mode b	4.6	864.58	0.65	3
activity 2_8	mode a	0.47	546.36	0.85	8
	mode b	0.05	235.74	0.89	1
	mode c	0.17	432.98	0.53	6
	mode d	1.3	293.81	0.5	18
activity 3_9	mode a	2.54	166.46	0.64	19
	mode b	3.86	805.01	0.52	19
	mode c	4.48	770.36	0.59	19
activity 4_10	mode a	2.15	859.77	0.88	20
	mode b	4.15	940.77	0.66	2
	mode c	2.03	534.74	0.52	11
	mode d	4.27	34.37	0.88	14
activity 5_10	mode a	4.52	490.12	0.97	9
	mode b	2.09	294.1	0.76	17
activity 6_11	mode a	3.92	644.31	0.65	12
	mode b	3.13	745.04	0.92	8
	mode c	1.96	237.48	0.6	11
	mode d	2.8	802.93	0.6	9
activity 7_20	mode a	0.06	714.32	0.77	7
	mode b	1.47	406.23	0.97	20
	mode c	2.83	259.48	0.77	11
	mode d	2.86	42.28	0.83	11
activity 8_12	mode a	3.28	410.33	0.68	16
	mode b	3.11	760.32	0.66	2
	mode c	1.01	179.53	0.8	8
activity 9_13	mode a	2.69	220	0.63	4
	mode b	2.67	876.65	0.55	2
	mode c	0.33	836.54	0.96	7
	mode d	3.51	711.22	0.79	19
activity 10_14	mode a	3.36	35.84	0.65	8
	mode b	3.2	0.93	0.53	14
	mode c	3.33	806.1	0.93	17
	mode d	2.24	596.3	0.97	11
activity 11_15	mode a	0.42	923.99	0.96	1
	mode b	1.17	980.37	0.78	3
	mode c	0.26	323.85	0.65	5
	mode d	2	232.69	0.76	17

Table B.4.A (continued)

	Mode	Cost	Emergy	alpha	Time
activity 12_16	mode a	2.02	276.45	0.64	10
	mode b	4.33	869.67	0.82	4
	mode c	2.54	448.7	0.67	17
	mode d	3.24	579.27	0.76	15
activity 13_16	mode a	1.07	291.07	0.84	1
	mode b	0.68	195.16	0.62	6
	mode c	1.16	705.33	0.54	19
	mode d	2.92	36.29	0.69	12
activity 14_17	mode a	4.73	816.96	0.51	17
	mode b	2.04	562.55	0.78	20
	mode c	1.76	299.61	0.72	1
	mode d	1.52	841.05	0.57	4
activity 15_18	mode a	3.78	568.38	0.59	17
	mode b	3.27	594.91	0.69	18
activity 16_20	mode a	4.73	873.4	0.56	4
	mode b	4.74	575.04	0.51	6
	mode c	2.43	301.24	0.94	8
	mode d	3.45	413.23	0.71	8
activity 17_19	mode a	2.95	46.25	0.56	15
	mode b	4.67	468.26	0.89	2
activity 18_19	mode a	3.61	507.9	0.51	12
	mode b	3.85	152.04	0.82	5
	mode c	0.11	266.31	0.53	4
	mode d	0.1	735.41	0.98	16
activity 19_20	mode a	3.64	170.25	0.98	15
	mode b	3.72	113.71	0.95	10
	mode c	4.49	915.59	0.6	3
activity 20_21	mode a	4.02	694.61	0.53	19
	mode b	4.64	948.68	0.91	18
	mode c	4.34	486.97	0.58	17
	mode d	4.45	537.2	0.64	11
	mode e	0.76	707.47	0.74	20

Table B.4.B Precedence Relationship and beta Figures for CE4

Predecessor	Successor	beta	Predecessor	Successor	beta
activity 1_8	activity 8_12	0.05	activity 12_16	activity 16_20	0.63
activity 2_8		0.95	activity 13_16		0.37
activity 3_9	activity 9_13		activity 14_17	activity 17_19	
activity 4_10	activity 10_14	0.64	activity 15_18	activity 18_19	
activity 5_10		0.36	activity 7_20	activity 20_21	0.06
activity 6_11	activity 11_15		activity 16_20		0.39
activity 8_12	activity 12_16		activity 19_20		0.56
activity 9_13	activity 13_16		activity 17_19	activity 19_20	0.93
activity 10_14	activity 14_17		activity 18_19		0.07
activity 11_15	activity 15_18		activity 20_21	-	

B.4.2 CE4 Solutions

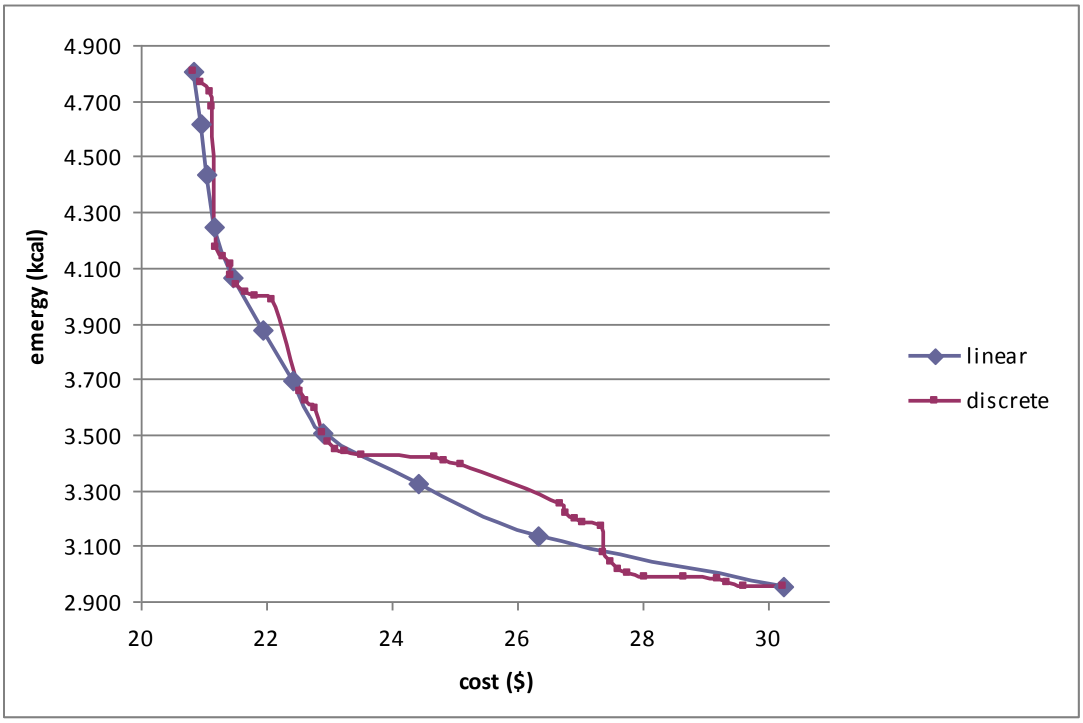

Figure B.4.A Linear and Discrete Solutions for CE4

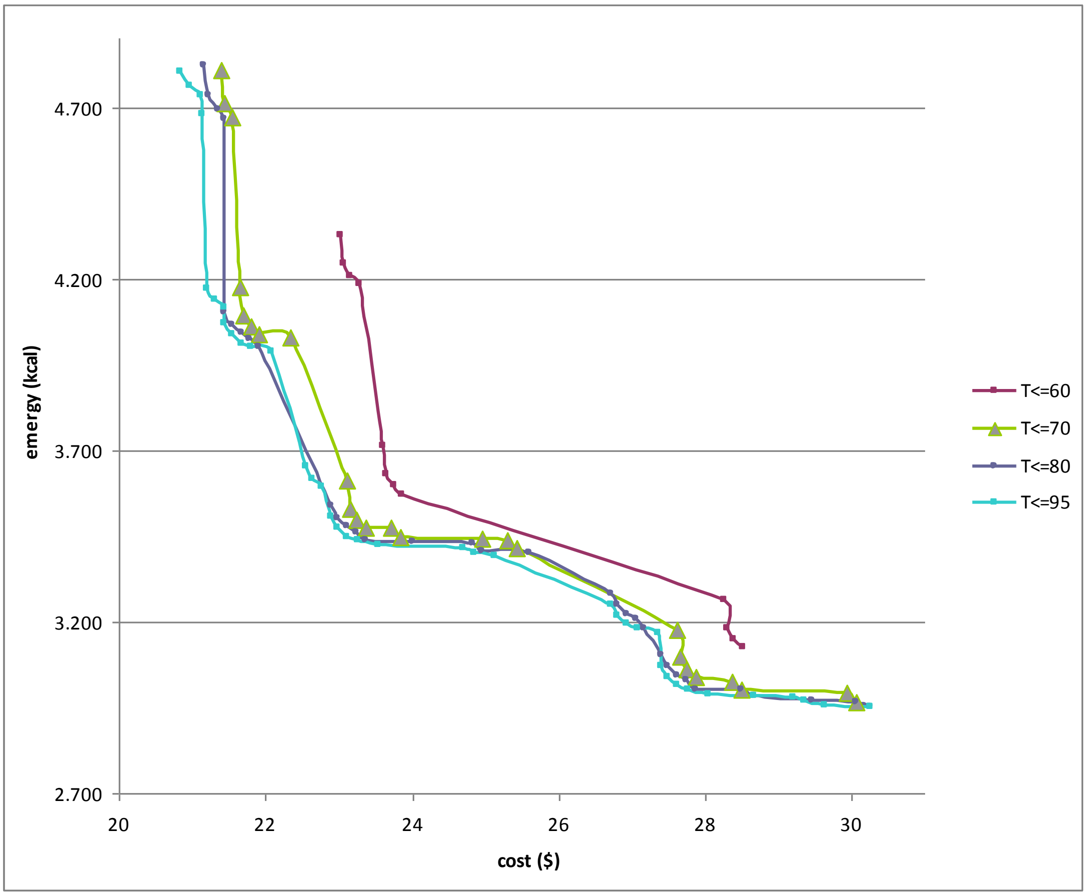

Figure B.4.B Time/Emergy/Cost Solutions for CE4