A Proactive Framework within a Virtual Engineering Environment for Assembly System Energy Optimisation

By

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Declaration

This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree.

The work presented (including data generated and data analysis) was carried out by the author.

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Abstract

The concept of sustainable manufacturing is increasingly becoming a new trend in the today’s industry, induced by the environmental issues such as global warming and scarcity of natural resources, and subsequently customer and government interactions. This leads to introduce the impacts of the industrial activities to the environment as crucial requirements, side by side to traditional ones such as production cost, product quality and quick response to market demands. Comparing to other sectors among the industry field, the manufacturing sector is a key player in this eco-friendly transformation because of its massive impacts contribution. Energy optimisation is one of the most important features of the developing sustainable manufacturing system; since it has very strong influence on limiting these bad impacts, which often cause increase in the operational cost.

This research describes a framework, and its software, which proactively predicts and then optimises the energy consumption of an assembly machine throughout its lifecycle, in particular at the design phase where alternative machine designs and configurations can be examined and evaluated based on their potential energy consumption. The proposed framework benefits from the component-based approach as the modular component is the basic entity to be (re)used and (re)configured throughout machine development process, and virtual engineering technology which facilitates investigating component and machine behaviours virtually with high degree of reliability and robustness throughout its lifecycle.

The aim of this research is to link assembly machine process parameters to energy prediction and optimisation requirements in a virtual environment to enable different alternatives to be examined and investigated before the physical build of the machine.

For proof of concept demonstration, a case study of a pick-and-place automatic workstation is presented. The energy consumption optimisation is achieved by optimising components motion control and station sequence of operation. In the case study, a number of experiments has been conducted to compare alternative designs and configurations against the original design. The results showed energy saving up to 27%, in spite of number of limitations, comparing to the original design by redefining 1) the component motion profile, 2) mode of operations, 3) start time, and 4) machine trajectory.

Keywords: *component-based approach, virtual engineering, energy prediction, energy modelling, energy optimisation, assembly machines, manufacturing systems.*

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To My Family

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Energy optimisation has become a very important topic in industry since the beginning of this century; shortage of energy resources, rising energy prices and strict regulations and legislations put more pressure on manufacturing firms to become more eco-friendly. Manufacturing industry is at the focal point of this new trend since manufacturing activities are the largest energy consumers and emission producers in the industrial field which also includes: the mining, agriculture, forestry, construction and fisheries sectors [82].

Energy cost rises globally due to scarcity of fuel accompanied by increase in demand which have led to increase in wholesale prices. Additionally enormous infrastructure investments are not carried out in an endeavour to accommodate environmental and climate change policies [7].

Existing manufacturing systems that do not comply with the new sustainability requirements will become obsolete due to governmental regulations and customer awareness. Upcoming manufacturing systems will certainly be founded on existing good practices and technologies. Future manufacturing must, however, deal with the pressing sustainability-related issues, forming new principles and characteristics. A life-cycle approach is needed to implement Sustainable Manufacturing systems, from raw material extraction, design, operation, and end-of-life. The negative impacts on the environment must be assessed properly by reliable sustainability metrics which can lead to the identification of optimisation opportunities and their implementation.

The automotive sector in particular has a pivotal role in this process since its factories are considered as high-intensity energy consumers and emission producers. Furthermore, the automotive industry stands as one of the most essential pillars of a modern economy. These facts show why advancements and shifts in manufacturing are often incited first by automotive firms. Automotive manufacturers have indeed adopted a range of sustainable practices and goals. For example; in 2016, Ford Motor Company has improved its global energy efficiency by 25% compared to that in 2010. The previous has been accompanied by reduction in CO_2 emissions by 26.5% compared to 2010 figures [30].

This research seeks to realise proactive and effective framework to enable energy efficient assembly activities, leading to more energy efficiency in the manufacturing industry. To reach this end, this research aims to promote the energy efficiency at the component and machine levels by extending the capabilities of current virtual engineering (VE) tools that benefit from component-based approach. This is centred on better integration of currently non-coupled machine and process design parameters, energy prediction and optimisation methods, and energy monitoring and management techniques.

1.2 PROBLEM DEFINITION

It is currently very difficult to provide fairly accurate answers to some critical questions related to energy usage of a machine before it has been physically built. Examples of these critical questions can involve: what the peak usage will be, what opportunities there are for energy reduction via design changes or optimisation of the process. This situation is incompatible with dire sustainability needs and the increasing energy prices.

Even if a machine energy consumption is modelled, it is still difficult to know whether what has been modelled at the machine design phase is what will be consumed at the operation phase, as these are currently non-coupled engineering activities. Discussions with machine builders have highlighted that different machine designs can have very different energy usages. Thus, linking machine design parameters to energy requirements will enable machine builders to choose the most energy efficient operation, which is strongly needed in a readily applicable form.

Energy monitoring and management techniques, widely used in industrial plants to measure machines' energy usage during the operation phase, are essential to identify the inefficiency in current manufacturing operations. However, relying on these techniques alone renders them often reactive, disruptive and incurring of preventable cost, time and risks. This has created a pressing need for proactive measures, at the machine design phase, capable of bridging the shortfalls of the former reactive practices.

Today's technologies offer a wide range of non-coupled developments; such as component-based approach, virtual engineering technology, energy modelling methods, energy optimisation methods, and energy management techniques. These developments have potential roles to play in achieving the engineering of more sustainable manufacturing. There is a potential for such developments to be integrated together to form a new engineering framework and new sustainable manufacturing paradigms, particularly in the context of energy optimised and reusable components.

1.3 RESEARCH MOTIVATION

The recent trend in industry in general and manufacturing in particular towards sustainability puts pressure on manufacturers to make their production facilities more environment friendly. The incentives of this trend are threefold: the environment, the society and the economy. These three incentives are interrelated as much as they are interdependent. When customers' awareness has been raised to notice the negative impact of industry on the environment, governmental regulations that protect the environment has been put in place to ensure that manufacturers conduct their activities in an eco-friendly manner. Although there have been some improvements in this regard, there are more sustainability improvements to be achieved by the manufacturing firms.

It has been estimated that process and production optimisation with respect to energy consumption could save 15 – 20%, with another 16% savings expected to be attained by logistics optimisation [26]. These savings can be achieved by redesigning process plans, redesigning machine hardware and software, replacing machine parts by more efficient ones, replacing auxiliary parts with more efficient alternatives.

Virtual Engineering (VE) is one of the powerful technologies that is heavily involved in the industrial activities. However, it needs to be exploited to promote the energy efficiency of these activities. Since the late nineteen sixties, when computers started to contribute effectively to industry, engineers and computer scientists have progressively computerised all aspects of manufacturing operations across all levels.

By using VE tools, products can be designed and validated, processes can be planned and verified, and changes can be accommodated easily, quickly and efficiently. Therefore, the vision of this research is to create a framework that enables energy consumption to be accurately and quickly quantified for each and every step throughout the assembly system lifecycle and process development. This can be achieved if the design parameters and the required data are linked in a VE development tool. Hence, one can easily investigate alternative designs and make comparisons and alignments.

There is an urgent need for such proactive framework and its associated tool that can predict these important values, provide important indications about the characteristics of the manufacturing activities from energy perspective, and investigate potential improvements to the related processes. However, such tool is currently unavailable neither to automation suppliers or machine builders. Current tools can reactively measure, monitor, analyse, manage and project the energy consumption data, but cannot proactively predict them in the early design phase, where most benefits can be achieved, which gives the proposed framework its value over the existing ones.

1.4 RESEARCH FOCUS

Automation Systems Group (ASG) at the University of Warwick has conducted research on the component-based approach for the development of manufacturing systems. Leading manufacturers, machine builders and automation suppliers such as Ford Motor Company UK, Jaguar Land Rover, Schneider Electric and Thyssenkrupp System Engineering have collaborated in this area of research. The primary objective of ASG research is to develop robust engineering approach to enable improving manufacturing systems within the automotive industry by developing the engineering tools shown in figure 1.1.

Component-Based Energy Optimisation (CBEO) framework has been created as a part of ASG research at the University of Warwick. The group has conducted research on component-based approach of automation lifecycle in manufacturing. A key aspect of this research is a 3D-based virtual engineering tool designed to virtually build production machines out of a generic set of components and to validate and optimise them before the physical build.

Figure 1.1 shows an overview of the research and development work of ASG. The green Energy Optimisation box and the green arrows indicate the specific areas of the author’s work. The focus of the author’s contributions was realising the novel CBEO framework and its Energy Optimiser tool to enable energy prediction and optimisation of assembly system throughout its lifecycle, particularly at the design phase where most benefits can be achieved in terms of minimising cost, time, risk and disruption. Details about the conceptual design will follow in sub-section 3.3.1.

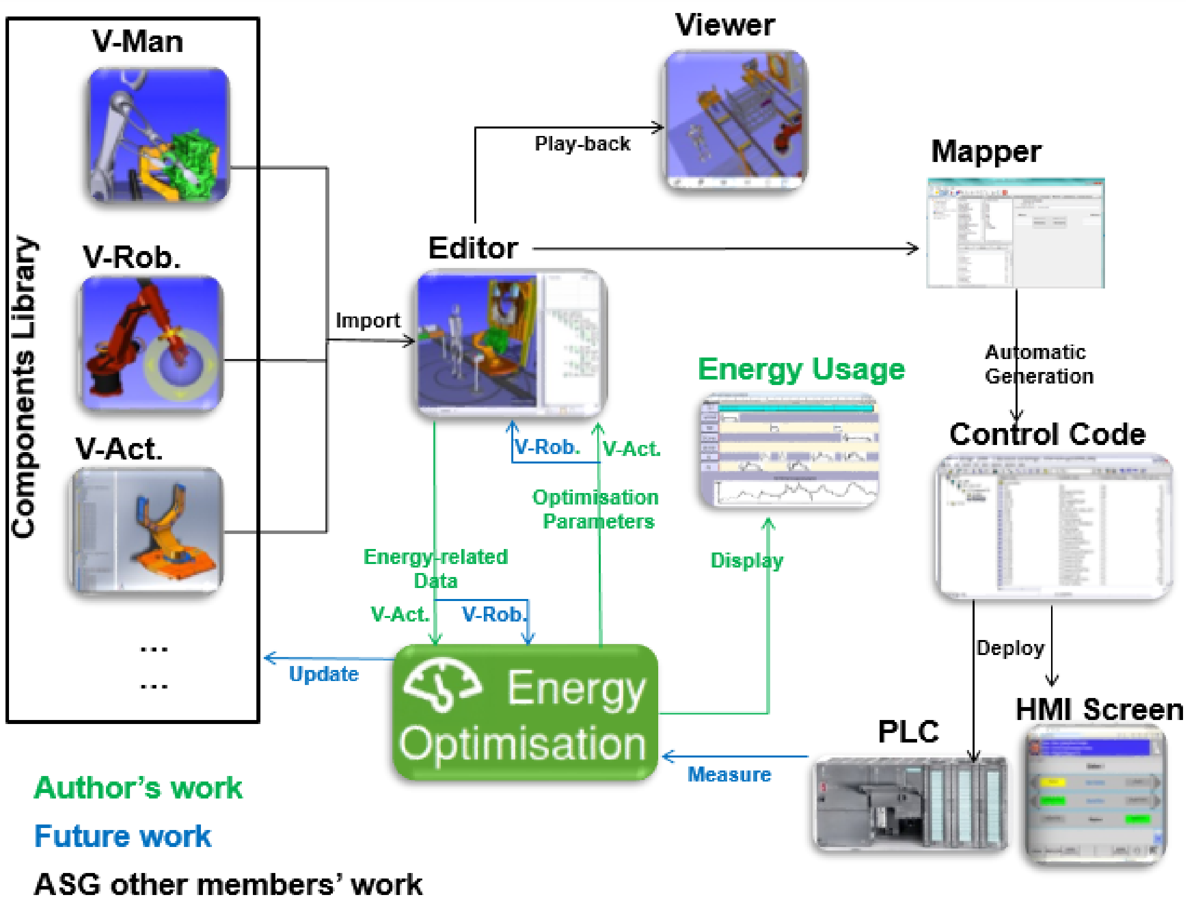


Figure 1.1: Development work conducted by the author, future work, and ASG other members' work

The vueOne editor enables the machine designer to create virtual components by defining their physical geometry and control behaviour, and then assemble them to build complete manufacturing systems. The modelled components are stored and retrieved from the Component Library. V-Rob, which mimics the operation of industrial robots, can be added to the manufacturing system model, as well as V-Man, which mimics human operators in manual and semi-automatic manufacturing operations. Energy optimisation tool requires the energy related data of the actuator components in the modelled system in order to predict their energy consumption and then apply the optimisation parameters into the virtual system.

To validate the energy-optimal virtual machine modelled in vueOne editor, vueOne viewer visualises and plays back machine operations in 3D format. Once the machine is validated, its predicted energy consumption can be displayed, and the PLC and HMI screen can be automatically generated and deployed into a physical PLC.

Actual energy measurements of the real system are required to compare them with the predicted energy consumption of the virtual machine in order to tune the energy models and update the

Component Library. Detailed explanation of Energy Optimiser tool design and operation is available in sections 4.4 and 4.5.

The research presented here includes the development of a framework which will support profound understandings of the implementation of a more energy efficient manufacturing operations. This framework features the provision of an eco-friendly platform that allows interaction between various components throughout the machine life-cycle and across process development levels.

The specific contribution of this research is to develop and implement the CBEO framework and its Energy Optimiser tool. It seeks to achieve this by integrating currently non-coupled energy monitoring techniques and energy modelling and optimisation methods at the component and machine levels, on the basis of the established Internal Model Control (IMC) theory, and by benefiting from and extending the powerful capabilities of the VE technology.

Furthermore, in order to benefit from CBEO framework, virtual industrial components must have energy-related characteristics such as physical and kinematical characteristics which determine the consumed energy due to the desired motion profile, operation mode, trajectory and control logic behaviour. CBEO framework allows the representation of the predicted energy consumption of the real system regardless of its complexity.

The Energy Optimiser tool results are validated by comparing them with the actual measurements on the shop floor. This validation allows profound insights into the components influence on the operational status of the overall system, and the need for the proposed CBEO for tuning to get the best possible results that fulfil processes requirements.

Finally, the CBEO should be fully integrated with the virtual engineering tool, veuOne, developed by ASG in order to exploit and extend its well-defined modelled components. Once this new validated feature is added to the existing veuOne for virtual visualisation and process planning purposes, the same energy information will be available and reusable to predict the energy consumption for any new machinery and hence facility to be built up from these components at any level of process development. Ultimately, following this argument, an important sustainable manufacturing requirement can be met.

1.5 RESEARCH HYPOTHESIS

The core hypothesis of this research is that: if energy consumption of a machine is accurately predicted and then optimised within a VE tool at the design phase, the manufacturing activities of this machine will fulfil the requirements of sustainable manufacturing at the operation phase. In other words, since machine design and operation parameters are well-coupled within such a VE tool, the predicted energy consumption of the machine at the design phase should closely match the measured consumption at its operation phase.

Furthermore, the same energy practice information of the machine components can then be (re)used to optimally parameterise the same machine to be reconfigured/redesigned, or a new machine to be designed and built using some or all of these well-defined components.

1.6 RESEARCH AIM AND OBJECTIVES

The purpose of this work is to improve the efficiency of assembly machine activities to fulfil the next-generation sustainable manufacturing requirements. In order to build a framework for sustainable manufacturing that is able to minimise the energy consumption during machine operation, there is a high need to extend the capabilities of the component-based approach and VE tools to include energy related data of the components and processes.

Through the development this framework, the author aims to promote best practices for system reuse, energy efficiency and modularity towards rapid responsiveness within the sustainable manufacturing domain.

The research objectives are listed below:

1. Examine and identify the common features of the existing approaches and practices to energy efficient manufacturing and their implementation and shortfalls.
2. Define suitable logical abstractions that are required to best address end-user requirements.
3. Adopt an approach that supports the reuse of modular machine components for improved energy efficiency.
4. Extend the capabilities of the existing veuOne VE tool to include the required energy related data of actuator components and machine operations in order to accurately predict and then optimise machine energy usage.

5. Develop a novel proactive, comprehensive and applicable energy prediction and optimisation framework to improve the efficiency of assembly machines throughout their lifecycle.
6. Develop a novel engineering tool for energy prediction and optimisation at the component and machine levels.
7. Implement a prototype system to validate the developed framework and its tool, hence the research objectives.

1.7 RESEARCH METHODOLOGY

A brief description of the phases of this research is listed below:

- Phase 1 – Literature and technology review
  The first period of this research was spent in reviewing and critically analysing the academic literature and industrial practices and technologies in order to accurately define the problem and identify the gap between what the need is and what is available to fulfil this need.
- Phase 2 – Specifications development
  Specifications, features and outcomes of this research and the developed CBEO framework have been driven by industrial requirements. Valuable discussions and meetings were held with manufacturers, machine builders and system integrators, and automation suppliers to identify the requirements.
- Phase 3 – Methodology development
  In this phase, a proactive, comprehensive and readily applicable CBEO framework has been developed to bridge the gap between end-users' requirements for energy efficient assembly machines and the current reactive engineering practices. The proposed CBEO framework has been further developed into an engineering tool to enable energy prediction and optimisation of assembly machine throughout its lifecycle.
- Phase 4 – Application verification
  The purpose of this phase was to verify the outcomes of the proposed CBEO framework against an industrial application. Experiments have been performed on an SMC pick-and-place machine of the Automation Systems Workbench at Warwick University, to

compare the virtually predicted and optimised energy consumption with real machine consumption.

- Phase 5: Evaluation and future improvements of CBEO framework

  In this phase, the outcomes of the evaluation process enabled the author to highlight a number of issues to be improved within the proposed CBEO framework before it gets fully integrated to the vueOne VE tool.

  CBEO has been tested by doing a number of experiments on the SMC station and comparing the results with the ones that were predicted. A number of different scenarios have been implemented to capture different factors that have influence on energy usage.

1.8 THESIS STRUCTURE

The rest of this thesis is structured as follows: chapter 2 describes the current problem and need, and critically reviews the industrial practices and relevant research. It also identifies the limitations of current manufacturing practices. To overcome these limitations and fill the gap between business requirements and current practices in the context of sustainability, chapter 3 proposes a holistic framework based on the IMC theory. This proposed state-of-the-art framework integrates reactive engineering activities with non-coupled optimisation methods. For proof of concept and evaluation of proposed framework, chapter 4 analyses and compares the actual measurements and the predicted results of the machine under study. Finally, chapter 5 summarises the work conducted in this research and highlights potential improvements and future directions.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Manufacturing systems simply transform raw materials into products using physical mechanisms. They survive only if they gain value which could be income, reputation and so on. They function to meet customers' requirements by manufacturing the required products [28]. Over the last century, the manufacturing industry has witnessed the emergence of several paradigm shifts to cope with the evolving economic, social and recently environmental requirements.

On one hand, more energy is constantly needed to perform the industrial and, in particular, the manufacturing activities. On the other hand, this demand raises the worldwide concern about the dire environmental issues, such as climate change and depletion of natural resources. In the near future, the demand for energy is strongly expected to increase around the globe. This increase will be accompanied by disappearing resources, and consequently the price of energy will raise. The industrial sector consumed about 54% of the total global energy in 2016, more than any other sector [13]. Thus, higher energy efficiency in the manufacturing systems could make a very important contribution to reduce the industrial sector share of energy consumption, and, consequently, the bad impacts to the environment.

The existing component-based reconfigurable manufacturing system is strongly nominated to potentially contribute to the formation of the future eco-friendly, sustainable manufacturing system. Its characteristics give it the potential to help meeting the requirements for sustainability.

The virtual engineering technology has a key role as an enabling technology for sustainable manufacturing systems, because of its powerful visualisation and optimisation capabilities throughout the entire manufacturing system lifecycle. For example, the energy required to perform an operation can be estimated, the amount of raw materials and potential emissions also can be predicted, or potential improvements can be foreseen by suggesting different processes [31]. Furthermore, visualising the energy flow for components and machines throughout their lifecycle offers a better understanding of their efficiency. In addition, it helps identifying any change in the energy consumption that occurs due to any change in machine parameters [65].

2.2 MANUFACTURING SYSTEMS PARADIGMS

A manufacturing paradigm, according to Koren, is a revolutionary integrated production model that arises in response to changing societal and market imperatives, and is enabled by the creation of a new type of manufacturing system [53].

The modern manufacturing industry has undergone several manufacturing paradigm shifts induced by changes in customers' requirements and changes in the complexity of the manufacturing environment [20]. Each paradigm has its own imperatives, enablers and principles. Developing a new paradigm, which meets new requirements and has the capacity to deal with the limitations of the existing paradigms, essentially relies on a new enabling technology, and then allows new imperatives to be addressed.

Many manufacturing paradigms have been introduced since the so called the industrial revolution. It is inaccurate to say that one paradigm is better than another without taking into account a specific situation in a specific enterprise. In order to understand the need of any new paradigm, one must first understand the principles, imperatives and enablers of the existing ones. Hence, one may consider the following widely adopted paradigms: 1) mass production, 2) lean manufacturing, 3) mass customisation, and 4) reconfigurable manufacturing, in order to analyse their characteristics and limitations, and therefore, their contributions to enable, the sustainable manufacturing paradigm.

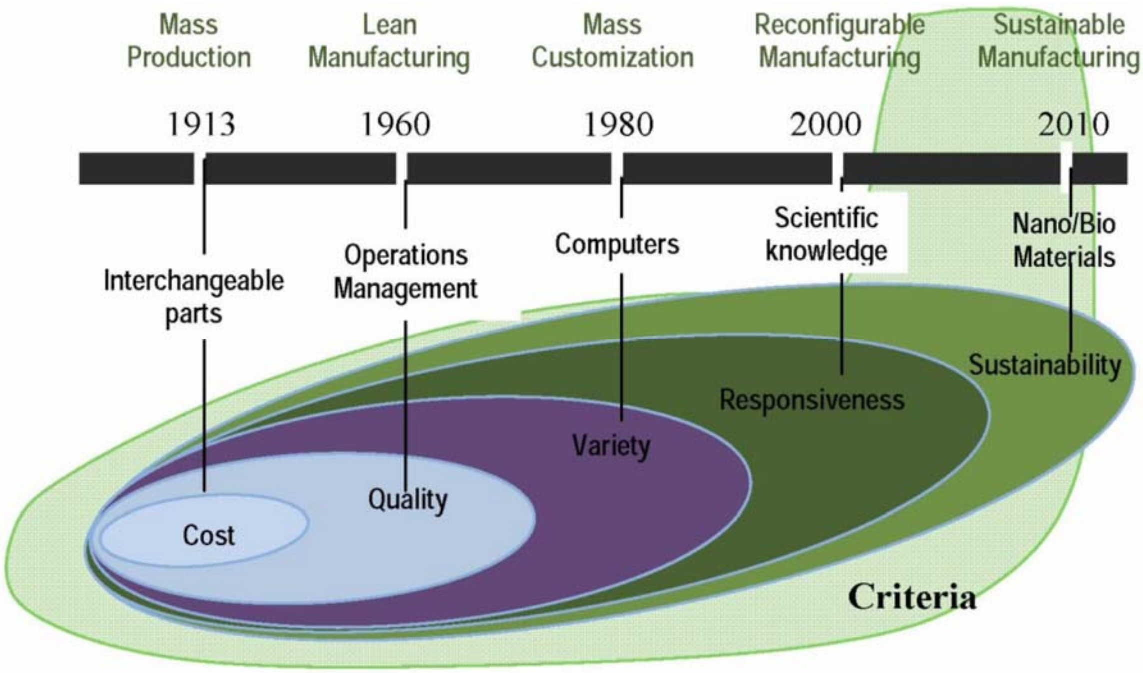


Figure 2.1: The evolution of the manufacturing paradigms [20].

2.2.1 MASS PRODUCTION

The operation of producing the highest possible standard of goods at the lowest possible cost using single-purpose machines was recorded in ancient Greece. This kind of manufacturing practice took more defined shape from the eighteenth century in England and then Europe. Over the last century, it had been the undisputed manufacturing behaviour till the late sixties [77].

The main principles of mass production manufacturing can be listed down briefly [19]:

- Dividing carefully the whole production operation into simple, repetitive, specialised hand-free tasks.
- Standardising the components or parts to allow the large production runs of parts that are readily fitted to each other without adjustments.
- Using single-purpose machines with specialised materials and processes to minimise efforts required and maximise the output per unit of investment.

The major disadvantage of the mass production systems is they are inherently inflexible; if any unplanned situation occurs, then the system may encounter serious problems to accommodate it and may lead to severe consequences, primarily, high increase in the cost. For an instance, as the system is designed to work most efficiently at a specific rate, if the required production level goes below this rate, machines and labours are being inefficiently used. On the other hand, if the level goes over this rate then labours work overtime and machines maintenance cannot keep up leading to breakdowns.

From the energy consumption perspective, over half of consumed energy goes to non-productive activities (start-up, shut-down, idle, etc.), in mass production systems. It is reported that the energy consumed by non-manufacturing activities may reach to 85% of the actual whole energy required to manufacture a product [63, 18, 58]. This implies that a significant amount of energy could be saved by employing better system-level operational planning and machine-level energy optimisation.

2.2.2 LEAN MANUFACTURING

Although the mass production systems worked very well in the United States' market, it was not the case in other countries. The economic difficulties in Japan after World War II, and the cultural differences induced the Japanese manufacturers, after deep understanding of mass production techniques, to think about alternative practices.

The concept of producing a large variety of products in small volumes with minimum non-value-added waste, which gives this system the name 'Lean', gradually emerged as the Toyota Production Systems started in 1948. Their multi-purpose machines enabled them to achieve this in a competitive manner by 1960, with customers able to demand more than a basic product [67].

Lean is a philosophy about delivering value from the customers' perspective, eliminating waste and continuously improving processes. Lean production systems aim at optimising objectives like cost, time and quality. Lean management is based on four principles [89]:

- Rather than producing as much as possible, customer demands pull goods or services through the manufacturing process. This minimises overproduction, inventory and ultimately working capital.
- Focusing on one single piece at a time minimises work in progress, process interruptions, and lead and waiting time while increasing quality and flexibility.
- Takt: Is how fast it is needed to manufacture a product to meet customer demand. Takt allows the balancing of work content, achieving a continuous flow and responding flexibly to changes in the marketplace.
- Mistakes happen but a lean system does not pass on defects from previous steps, they must be fixed before going on.

Generally, lean and green manufacturing systems considered to be more concurrent than consolidated [39]. Although lean system principles aim at eliminating waste over the system's lifecycle, the implementation of lean activities does not necessarily eliminate the energy waste.

Lean and green activities inherently cannot be optimally integrated at the higher levels of the manufacturing systems because of the current lack of relevant strategies that are directly related to quantitative waste reduction at lower levels of the system [45]. Moreover, their primary focus, definition of waste, performance metrics, and the used techniques have some different dimensions between them [39]; for example, modelling dimensions may be completely different or conflict with one another.

2.2.3 MASS CUSTOMISATION

Mass customisation (MC) is a production strategy focused on the broad provision of personalized products and services, mostly through modularised product/service design, flexible processes, and integration between supply chain members [37].

From the costumer perspective, MC aims to provide customer satisfaction with increasing variety and customisation at reasonably low cost and with short lead time [84]. From the manufacturer perspective, MC aims to achieve a balance between product standardisation and manufacturing flexibility. By adopting the MC technique, manufacturers are able, to some extent, to stay competitive in a more uncontrolled and unstable global market.

The huge leap in the computer science in the 1980s played a key role in the manufacturing industry. This role can be noted in using numerical control machines, general-purpose automation and industrial robots that significantly increase systems flexibility. Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) allows more rapid product and process designs and modifications generated to response to customer requirements [71].

Implementing the MC has double-side effects on the environment sustainability. On one hand, a product is only manufactured after receiving an order from the customer, a so called make-to-order business model principle, which means overproduction is fundamentally prevented. This results in lower energy consumption for the overall production in comparison with the mass production [72].

On the other hand, the variety of products offered by the MC requires high process flexibility. The high number of different manufacturing processes, makes the MC difficult to be optimised with respect to energy consumption [25]. It is therefore difficult to judge whether the MC manufacturing systems are eco-friendly or not.

2.2.4 RECONFIGURABLE MANUFACTURING SYSTEMS

Global markets have witnessed dramatic changes since the new millennium; high frequency introduction of new products, increasing fluctuation in product demand and new process technologies give an indication about the shape of the new markets. Consequently, manufacturers and academics (including perhaps most notably Professor Yoram Koren) reacted to these changes by proposing a new form of scalable and reconfigurable manufacturing system [54].

According to Bi [23] an RMS has an ability to reconfigure hardware and control resources at all of the functional and organisational levels, in order to quickly adjust production capacity and functionality in response to sudden changes in the market or in the regulatory requirements. The concept of an RMS is also similar to the concept of component-based manufacturing systems [44]. RMS aims to provide the functionality and the capacity that is needed when it is needed; i.e. both its functionality and capacity are not fixed like other systems. RMS basic principles are [54]:

- The RMS is designed for adjustable production resources to respond to forthcoming needs. The RMS capacity is rapidly scalable in small, optimal increments. The RMS functionality is rapidly adaptable to the production of new products.
- To enhance the speed of responsiveness of a manufacturing system, core RMS characteristics should be embedded in the whole system as well as in its components (mechanical, communications and controls).
- The RMS is designed around a part family, with just enough customised flexibility needed to produce all parts in that family.
- The RMS contains an economic equipment mix of flexible (e.g., CNC) and reconfigurable machines with customised flexibility, such as Reconfigurable Machine Tools, Reconfigurable Inspection Machines, and Reconfigurable Assembly Machines.
- The RMS possesses hardware and software capabilities to cost-effectively respond to unpredictable events — both external (market changes) and intrinsic events (machine failure).

Table 2.1 below shows the key characteristics of RMS.

Table 2.1: The key characteristics of the reconfigurable manufacturing system [61]

1.	Modularity	Design all system components, both software and hardware, to be modular.
2.	Integrability	Design systems and components for both ready integration and future introduction of new technology.
3.	Convertibility	Allow quick changeover between existing products and quick system adaptability for future products.

4.	Diagnoseability	Identify quickly the sources of quality and reliability problems that occur in large systems.
5.	Customisation	Design the system capability and flexibility (hardware and controls) to match the application (product family).
6.	Scalability	The ability to change the machines' production throughput by altering or augmenting the component in the machine.

Among various technologies and processes that enable RMS, open-architecture control (reconfigurable software) and modular machines (reconfigurable hardware) are substantial enabling technologies [62]. Section 2.5 explains how the Sustainable Manufacturing System gains benefits from the RMS.

2.3 THE NEED FOR SUSTAINABLE MANUFACTURING

Today both manufacturers and costumers are becoming more conscious about the environment; both of them really do understand the problem and start to behave more responsibly. Although the vast majority of small and medium enterprises (SMEs) have not yet addressed sustainability because of their short-term survival issues, the efforts of some high volume manufacturers, such as automotive manufacturing firms, have shown tremendous improvements. For instance, in 2013, Ford Motor Company announced their goal to minimise their facilities' CO_2 emissions by 30% by 2025, compared to 2010 baseline, building on the 31% reduction they achieved from 2000 to 2010. Furthermore, Ford managed to reduce their facilities' water usage by 62% from 2000 to 2012. Also Ford reduced the amount of waste sent to landfill by 40% from 2007 to 2011, and the energy consumption of their worldwide facilities by 30% from 2008 to 2013 [29].

The worst scenario was predicted by Meadows in his model called world3-03 [60], which shows a critical collapse of the natural resources, and hence the production and population systems consequently. Thus, behaving friendly to the environment is no longer inferior. Also, improving the energy efficiency of the manufacturing system means improving the business profits by reducing the operational cost. For example, improving the energy efficiency means saving in the energy bill and avoiding the different types of fines. Also, it improves the business reputation by showing responsibility towards the society and the environment, by for example, reducing the depletion rate of energy resources as well as reducing the harmful emissions.

Several initiatives on more energy efficient manufacturing are on-going. For example, the European Commission has put in place its Environmental Action Programme to 2020 in order to tackle the persistent sustainability challenges until 2020 as a prelude to the 2050 vision of a prosperous and healthy environment [5]. In this context, improving the energy efficiency of both small and medium enterprises (SMEs), and high volume manufacturers can help effectively to attain this vision. On the other hand, manufacturing systems that do not comply with the increasingly stringent governmental regulations, and the increasing customers' awareness of the environmental issues, will become obsolete.

There are many motivations and drivers to behave in an environment-friendly manner can be generally summarised in five drivers:

- Shortage of natural resources: Fossil fuel is the main source for world energy supply; oil supplies are estimated to last another 26 years assuming continuous compound consumption rate, similarly gas and coal for 28 years and 98 years respectively [80]. The situation gets worse if this rate gets increased because of every nation is ambition for economic growth.
- Global warming: There is a little debate that the Earth will warm during this century as a result of fossil fuel combustion. The Intergovernmental Panel on Climate Change (IPCC) has identified exponential increases in atmospheric concentrations of CO_2 as the dominant forcing agent for global warming [2]. Although expectations of the extent of this warming are primarily limited, the following equation $\Delta T = \lambda 5.53 \ln(C/C_o)$ forecasts the change in the global surface temperature, where ΔT is the temperature increase at a given year relative to a reference year; C and C_o are the CO_2 concentrations at that given year and in reference year respectively. The λ coefficient is the climate sensitivity; λ can assume values between 0.3 and 1.3 [2].
- Pollutions: Manufacturing activities generate considerable amounts of waste that are in main landfilled, discharged into surface water or burned causing dangerous health and environmental consequences. In 2014, official statistics shows that 11.12% of the total waste, 36.5% of greenhouse gas emissions, the European Union zone (EU-28) were generated by manufacturing industry [8].
- World population: The world population currently is over 7 billion people. It was 2 billion in 1927, and is expected to reach between 8.3 billion and 10.9 billion by 2050 according to United Nations, Population Division [1]. This increase in population leads

to increase in human activities which in turn increases depletion of more resources to meet their demands. This increase will lead to increases in wastes and emissions.

- Legislations and regulations: Since manufacturing operations are getting more deleterious to humankind and the environment, governments around the world are getting actively involved in the development of manufacturing systems that are able to limit these negative impacts. The point behind this governmental move, is to bring all parties (manufacturers, costumers, environment, etc.) into win-win situations, by funding researches and studies on sustainability, offering grants and prizes to industrial firms and raising the awareness of customers on one hand, and mandating eco-friendly regulations and legislations, revisiting standards and the requirements, and banning materials and processes in other hand [41].

2.4 SUSTAINABLE MANUFACTURING SYSTEM

According to the United States Department of Commerce, sustainable manufacturing is defined as the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound [11].

Sustainable Manufacturing Systems (SMS) involves complicated interactions between the environment, the economy and the society, and impacts on all of them. This is not only about environment-friendly products or processes; supply chain, enterprises, facilities, processes and products must also be considered in this manufacturing system. In this research we focus on the environmental aspects of sustainability, and the manufacturing activities at the machine level.

2.4.1 SUSTAINABLE MANUFACTURING METRICS

Developing metrics for SMS is essential to enable manufacturers to measure their systems' lifecycle performance toward the environment. These metrics enable design engineers to focus on specific areas at the design process [11]. The sustainable manufacturing indicators should be applicable, comparable and common [41]. They could be expressed in quantitative or qualitative, normalised or non-normalised numbers, and absolute or relative values [36].

SM indicators ideally should help the manufacturer to monitor progress over time, take actions against problems to improve performance, and identify any considerations that may be missing from earlier analysis to help get a fuller picture.

Currently there are no internationally agreed metrics for the SM. Moreover, there is a lack of any inclusive, open and neutral metrics for the SM. Selecting such metrics, that will inform performance analysis, is not a straight forward process like economic metrics selection, such as unit cost. Some initiatives have been carried out by some academics, international corporations and international organisations in this context. For example:

- Organisations: The Organisation for Economic Co-operation and Development (OECD) Toolkit [11], provides eighteen quantitative indicators (e.g. P2 recyclability (Products), O1 water intensity (Operations), I2 restricted substances intensity (Inputs) and so on) to help measuring the environmental impact of single facility activities for all types of manufacturing. However, some of these indicators can be extended to measure supply chain related impacts, and if the manufacturer wishes to measure the environmental impact at the overall enterprise level, then individual facilities indicators can be aggregated.
- Corporations: Ford Product Sustainability index PSI [10], it is the first index in the automotive sector. It provides eight (e.g. global warming, safety and cost) indicators that yield a result (non-single value) in line with the international standards such as ISO 14044:2006 Life-Cycle Assessment (LCA) standard. It measures the lifecycle environmental impact of the final produced vehicles.
- Academics: Reich-Weiser has suggested measuring SM in terms of energy scarcity, energy independency, material scarcity, water availability and climate change .It follows the ISO 14044:2006 standards on LCA [74].

2.4.2 LIFE-CYCLE ASSESSMENT (LCA)

The LCA is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a system throughout its lifecycle [6]. The ISO 14044:2006 international standard (first released in 1997, last reviewed and confirmed in 2016) defines the environmental impacts of products LCA.

LCA is a tool to assess the environmental impacts along the lifecycle (pre-manufacturing, manufacturing, use and post-use) phases of products and processes. This tool enables the assessor to model the enterprise from which the products are manufactured or in which processes operate. It allows the decision makers to make quantitative comparisons, which in turn allow them to more fully understand the risks, opportunities and trade-offs among the phases and the different impacts that occur at each phase.

LCA has four basic elements [52]:

1) Goal and scope definition (G & SD): It is like an introduction in which the valid rules for a specific LCA study are defined.
2) Inventory analysis (LCI): It models the system according the requirements come from G & SD.
3) Impact assessment (LCIA): It contains the impact categories that are subject to evolution.
4) Interpretation: According to ISO 14044:2006, phase of life cycle assessment is where the findings of either the inventory analysis or the impact assessment, or both, are combined consistently with the defined goal and scope in order to reach conclusions and recommendations.

Figure 2.2 shows the aforementioned four elements.

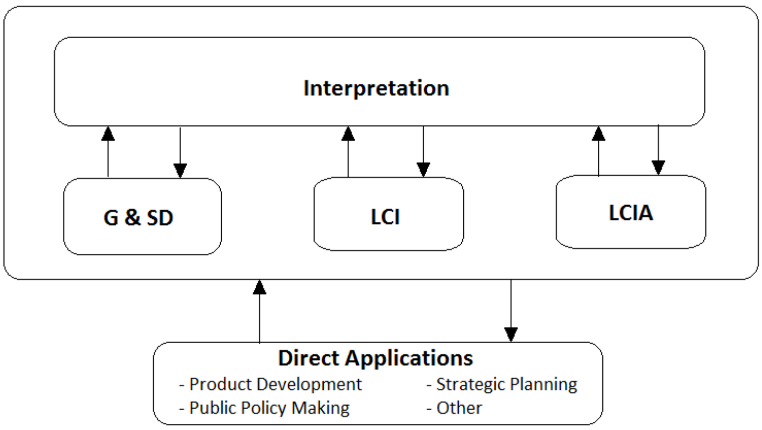


Figure 2.2: Elements of LCA (ISO 14044:2006)

Despite the fact that it offers a robust framework toward sustainability, LCA suffers from some limitations such as data uncertainty, time and recourse intensity for the sake of gathering inventory data, and modelling missing impact indicators. These limitations need to be spotted first in order to allow a researcher to cope with and improve this best framework [52].

2.5 PARADIGM SHIFT TOWARDS SUSTAINABLE MANUFACTURING

The requirements of the SM paradigm are unprecedented. The existing manufacturing paradigms have been developed for the sake of the conventional manufacturing requirements (cost, quality, time, etc.) but not for sustainability requirements. Although none of them meets the sustainability requirements, the existing paradigms are definitely going to contribute to any forthcoming and promising sustainable manufacturing paradigm.

It is more realistic to evolve the existing system paradigms guided by the concepts of SM to meet sustainability requirements. Extending the design and optimisation efforts on non-manufacturing activities at all levels (component, machine, facility, enterprise and supply chain), and along the entire lifecycle (design, build, commission, operate, maintenance and post-use) makes the manufacturing system more sustainable [20]. For instance, the traditional reusing, reducing and recycle activities at the product level that are applicable to materials and tools in the RMS must be extended to include recovering, redesigning and remanufacturing. At the process level, taking into account the reduction of energy and waste (and other sustainability indicators) by improving process planning, virtual machine simulation and commissioning, also it offers opportunities for realising more sustainable manufacturing.

As reported in the sub-section 2.2.4, the RMS paradigm is proposed to meet the uncertainties of the manufacturing system, and this objective is achieved as a result of the inherently control and component reconfigurability features. These characteristics give it the potential to play a key role in future manufacturing. They make it adaptable to changes. Virtual engineering tools have the potential to relieve the burden of complex planning and scheduling, components configuration/augmentation and hardware modelling and commissioning, cost and time effectively [21].

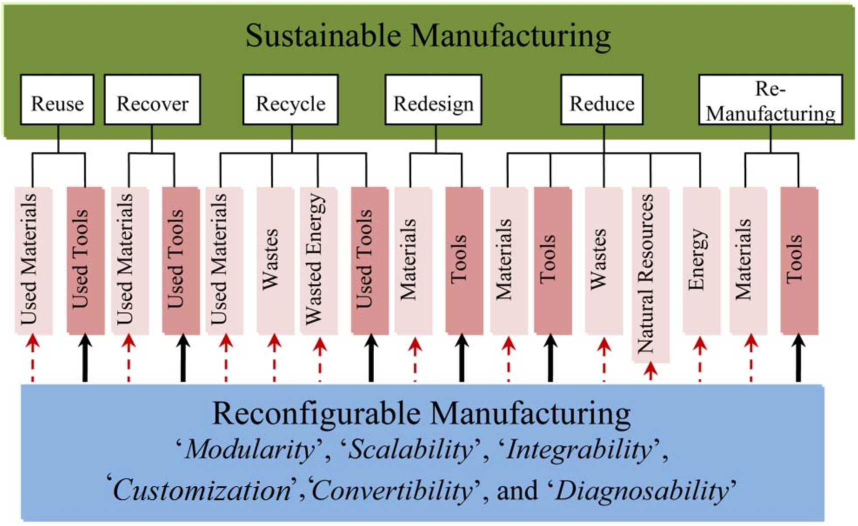


Figure 2.3: From the RMS paradigm to the SMS paradigm [20]

2.6 VIRTUAL ENGINEERING AS AN ENABLING TECHNOLOGY

The virtual engineering (VE) technology has evolved enormously over the last few decades, empowered the industry with powerful, fast and cost-effective tools for most aspects of product and process developments. Hence achieved high levels of competiveness. They can allow accurate evaluations in reduced time, cost, risk and effort [79].

The VE models can "mimic" or simulate a target system's (or object's) behaviour, response, appearance, and/or geometry with a degree of realism comparable to the actual system or object [27]. From the manufacturing system perspective, VE is typically utilised as described in the following sub-sections.

2.6.1 MODELLING AND SIMULATION

A model is a physical, mathematical or logical presentation of a system, entity, process or phenomenon. Whereas, simulation is a method for implementing the model over time [79].

Within a VE tool, an immersive model of a system can be created regardless how its parameters influence/interact with each other [65]. VE simulation and modelling capabilities provide representations of the geometry of parts and fixtures, evaluate the tool tolerances, part clearances, collision forces, reach angles, etc., and simulate the human motion in each process [79]. VE allows optimisation of the layout, manufacturing operations and can detect faults in mechanical configuration, which are costly to correct at later stages of the machine lifecycle.

Simulation can be used to resolve many of the uncertainties in the decision making process by representing the modelled system at various levels of abstraction. It also allows to investigate seamlessly, rapidly, and at low cost possible alternatives throughout the lifecycle.

2.6.2 PROCESS PLANNING

Process planning is an important application of the VE. It can give precise and clear visualisation of the sequence of machine operations and the layout i.e., how the product is to be moved and manufactured in a manufacturing facility [73]. Using product and resource data, VE tools can help create and validate the initial process plan, modify the plan for specific requirements, connect the product and resources to process steps, and carry out standard time studies and assign the job equally between resources. The operational sequence can then be visualised in a 3D format.

Considering Body in White (BIW) assembly planning for the automotive industry as an example, a 3D process planner enables system design and validation. Working directly with product data from engineering, BIW assembly planner can deliver to suppliers accurate 3D manufacturing assemblies of parts and assigned fasteners, sending early feedback to the design team about critical fasteners ensures that all weld points can be reached with a minimum number of weld guns keeping cost under control. The planner can then distribute all manufacturing assemblies and spot guns across the stations of a production line to maximise individual station capacities and minimise the overall cycle time [3].

2.6.3 VIRTUAL COMMISSIONING AND DEPLOYMENT

The objective of using the virtual commissioning is to optimise and debug the control system. During virtual commissioning, control logic is extensively tested including functions for emergency, safety, tracking, conditions check, communications and abnormal cases to avoid any risk of damage to real facilities. A practical study showed that 75% of the conventional commissioning time was saved by using the virtual commissioning first [46].

The virtual tests that are carried out at the virtual commissioning phase help to reduce the number of real tests significantly. This leads to shorten the time-to-market of the virtually commissioned system [75]. Another benefit of the virtual commissioning lies in the operation stage; when operators can be trained safely for mechanical and control systems' functions [51].

Once the virtual system operates satisfactorily with no faults and as planned, the control codes can then be downloaded to the physical target devices (PLCs, HMIs, motor drives, etc.).

2.7 CURRENT INDUSTRIAL PRACTICE FOR ENERGY OPTIMISATION

Reducing the energy consumption is increasingly becoming one of the top priorities for manufacturing industry. In 2016, the United Kingdom industrial sector consumed 17% of total energy [87]. Changing the nature of manufacturing procedures and techniques offers promise of more efficient and sustainable industry. Such change is being stimulated by several factors and incentives such as rising in energy costs and dynamic pricing, and climate impacts.

In order to identify the opportunities for energy optimisation for future manufacturing, understanding, investigating and evaluating the existing practices are perquisites. This understanding comes from monitoring, archiving and visualising consumed the energy consumption data. The operational energy data and historical reports can be used to analyse and then identify where potential efficiency improvements are needed.

Industry is using a number of methods and tools to identify the opportunities for energy optimisation. A brief overview of the most common practices that currently used in industry to monitor and optimise the energy consumption is given below.

2.7.1 ENERGY MONITORING

The energy consumption cannot be optimised unless it is measured and monitored. Several technologies that collect the energy data are being provided to manufacturers and machine builders by automation suppliers.

Some controllers, including certain types of Programmable Logic Controllers (PLCs) and Variable-Speed Drives (VSDs), have built-in energy measurement devices. These devices come with automated monitoring functions to calculate the consumed energy and the energy balance over time. Such automated monitoring is considered very powerful in terms of integrating measured energy data with manufacturing activities [12]. The recorded data is used to create reports that show the operating cost and the best operation practices. This data can also be shared over web servers or local networks with Supervisory Control and Data Acquisition (SCADA) systems for managerial purposes.

In addition, Human-Machine Interface (HMI) screens can be used to visualise the energy consumption at the machine, production line and plant levels. Some automation suppliers provide devices (e.g. circuit breakers and overloads) that can measure the energy consumed by various devices, thus allowing the mapping of energy consumption over a plant.

2.7.2 ENERGY MANAGEMENT

Energy Management: Referring to ISO 50003:2014 [4], energy management includes all the measures that are planned and implemented to ensure minimum energy consumption. The Energy Management System (EnMS) systematically records the energy usage and serves as a basis mainly for investments in improving the energy efficiency. The EnMS helps manufacturers to comply with the energy policy and to continuously and systematically improve its energy performance.

Energy management, according to the ISO 50003:2014, follows the PDCA (Plan, Do, Check, Act) cycle. The PDCA cycle provides a framework for the continuous improvement of processes or systems. It is a dynamic model; since the results of one cycle form the basis for the next one. This structure enables the continuous reassessment and optimisation of energy consumption with the goal of progressively reducing the cost.

- Plan: Establishing energy-saving targets, determining the strategy, identifying measures and responsibilities, providing the necessary resources, preparing the action plan.
- Do: Establishing management structures for maintaining a continuous process, undertaking improvement measures (for example efficient technologies/procedures).
- Check: Reviewing the level of target achievement and the effectiveness of the EnMS, collecting new ideas via energy audits. If necessary, consulting an external expert.
- Act: Strategic optimisation by consolidating the current energy data, audit results and new information, evaluating the progress with the help of current energy market data, deriving new objectives.

Potential energy saving opportunities can be evaluated reliably on the basis of the energy consumption reports.

2.7.3 ENERGY-EFFICIENT SCHEDULING AND PLANNING

This technique aims to associate each operation of a machine/line to its consumed energy. An optimum environmentally-oriented system-level scheduling and planning framework has not yet emerged but research in this direction is ongoing [58].

Some strategies are currently performed in the industry, such as load balancing, load shifting and sleep/off modes. Other strategies include switching some non-critical systems off in the case the overall energy usage is about to exceed the pre-set power usage threshold, run the most efficient production line based on operation efficiency, certainly, besides the production cost, and run the machines/lines at lower speed, or increasing their speed to maximise the productivity against time, labour and energy [12].

Other application for energy data records that they could help proactively in detecting the potential problems caused by potential machine/line based on the energy profile signature. It is vitally important strategy in case this excess in usage leads to break down some other machines or lines due to lack of power.

2.7.4 NETWORKED ENERGY MANAGEMENT

The ODVA (Open DeviceNet Vendors' Association) is investing significant efforts to define an Energy Management object to be added into its CIP (Common Industrial Protocol) objects' attributes, aiming to measure and reduce energy consumption both during idle time and production. An interoperable Energy Profile is also deployed to benefit customers who deal with different devices from different vendors. An Energy Profile is a way to easily identify energy capabilities that are implemented in a device. It defines energy and power related objects [24].

In case of bottle-neck or breakdown, weekends or shift change, or any other idle time, a Power Management object can be used to commands devices/machines/lines via a suitable controller or software to enter low-power modes. An Energy Management object can be utilised to prevent demand peaks during production. This operation typically happens hierarchally from small energy management clients at device level into typically machine, line and whole system level to manage the overall energy consumption [24].

In a similar manner PROFIenergy is a profile of the PROFINET communications protocol that allows the power consumption of diverse automation equipment in manufacturing (such as robot assembly cells, laser cutters and paint lines) to be managed over a PROFINET network. It controls energy usage during planned and unplanned breaks in production [9].

2.7.5 CURRENT ENERGY MANAGEMENT TOOLS

B.Data from Siemens, PMCS from GE, 4EE from Rextroth and PlantStruxture from Schneider are examples of the existing tools in the market. Few of the existing tools offer advanced functions beyond the basic monitoring, archiving, visualising and reporting functions. The advanced functions are capping power peaks, load balancing and computing projected energy costs.

It is worth noting that the aforementioned current industrial practices are considered as passive or reactive techniques, since they aim to reduce the energy usage of already established systems later at the operation phase. These fundamental characteristic makes these techniques are often disruptive, incurs more cost, time, effort and risk. Therefore, predicting and optimising the energy to be consumed by the envisioned system proactively at its design phase is expected to result in more energy and operational cost savings.

2.8 CURRENT ACADEMIC RESEARCH ON ENERGY OPTIMISATION

Ongoing research in academia is investigating the energy optimisation opportunities from different viewpoints. Here we summarise new research at the component/machine level that are not yet been implemented in the industry. It is worth noting that, the production line level is not reviewed here as it is out of the scope of this research. The main optimisation themes are idle time optimisation, path optimisation and acceleration optimisation.

2.8.1 IDLE TIME OPTIMISATION

The idle state of a component/machine is often an energy-inefficient state, where large amounts of energy are often wasted without production, degrading system efficiency. Shortening the idle time and introducing more energy-efficient modes during idle states are ways to enable energy optimisation. Inclusion of energy-efficient modes, complete shut-down or sleep mode, are expected to be feasible depend on: available idle time, the level of energy consumption during start-up and awaken-up, and the energy consumption during idle state.

In the case of complete shut-down, enough time should be allowed to switch the component back on before the beginning of its next task. To enable this inclusion, machine builders and automation suppliers should incorporate the required simple technological features in their components/machines [38].

2.8.2 MOTION PATH OPTIMISATION

A motion trajectory is defined by Riazi as a sequence of sampled robot machine poses at a given sampling rate. Each sample includes current position of the axes, the pose, and the specific time instance when the robot/machine reaches the pose. The path of a trajectory is defined by the sequence of poses that a trajectory follows, but without including the time instance when a pose is reached [76].

Servo-actuated mechanisms, including robots, are widely deployed in manufacturing due to their flexibility in adopting various programmable motion trajectories to suit the production goals. Energy-optimised trajectories for single and multiple degree-of-freedom mechanisms and manipulator systems have been proposed [40]. Several cost functions have been developed taking in account the dynamic and process constraints [68]. For instance, improving the energy efficiency of pick-and-place robot by means of time-scaling trajectory has been discussed, starting from the fact that 15-20% of the total working time of industrial robots in automotive industry is spent on Homing [69].

2.8.3 ACCELERATION OPTIMISATION

In some production operations the process and dynamic constraints, such as production rate and machine/component physical capabilities to adopt the new configuration may require the original paths and cycle times to be unchanged. In such cases, optimising the acceleration in motion profiles may be useful as an approach to achieve more energy-efficient movements.

Rapid acceleration/deceleration causes higher energy consumption. A simple but feasible method is to change the velocity profiles; for example, it is established that changing the velocity profile of a move from the triangular to the trapezoidal (where acceleration time, constant velocity time and deceleration time are equal) results in considerable amount of saving in the consumed energy [14]. For a given path, minimising the joints' accelerations result in more energy-efficient motion [76].

As with all the optimisation methods, software changes are typically desired but if the hardware does not support them, such as a motor drive that does not support the suggested more energy-efficient motion profile, then hardware redesign is necessary.

2.9 ENERGY CONSUMPTION PREDICTION AND MODELLING

Machine builders are required to include accurate energy consumption data in their components, machines and lines to enable their customers to manage operational costs and environmental performance during the operation. Unfortunately, there is no such robust tool in the market that can predict the energy consumption at the design phase at the component, machine or line levels. The importance of such a tool is its capability to examine different alternatives at the design phase, and then choose the most energy efficient design to be built.

Considerable efforts have been invested by many researchers in order to model or predict the energy usage of manufacturing machines. The existing energy consumption modelling can be classified into five main methods, which are described in the next sub-sections. The energy modelling methods are 1) mechatronics modelling, 2) power flow diagram, 3) thermal modelling, 4) mathematical modelling and 5) state-transition modelling.

2.9.1 MECHATRONIC MODELLING

Aims at deep understanding and accurate optimisation of the energy consumed in the physical system. Although it is an accurate method, yet it has limited applications because of very detailed parameters required. Also, it cannot be scalable or used generically in most cases [33].

In order to model the system accurately, the components behaviours, their interactions, their influences on the system performance, etc. should be well-known. Therefore the modelling process using this method is considered to be complex and time consuming [47].

2.9.2 POWER FLOW DIAGRAM

Or Sankey Diagram. Power flow diagrams can be used to give simple and general idea about the consumed energy in the corresponding components, machines or lines. This method gives no information about how the involved system is being used, and if this is constant or variable energy consumption over time [16].

2.9.3 THERMODYNAMICS MODELLING

Thermodynamics modelling method determines the theoretical minimum energy required to achieve any manufacturing task. This value is determined based on the fact that each manufacturing activity has heat and work interaction with other activities involved in the same operation, and with the surrounding environment in terms of reference pressure, heat and chemical compositions. Thus, the system behaviour can be modelled using the 1st and 2nd laws of thermodynamics, and metrics, including the consumed energy [42].

This method also aims to understand and analyse the system efficiency based on Energy, of 1st thermodynamics law, and the more accurate but complex, Exergy, of the 2nd law of thermodynamics [50]. Although this method is effective in comparing the relative efficiency of different manufacturing systems, it has limited applications as it needs hard to attain, unattainable or even unknown parameters [78, 70].

2.9.4 MATHEMATICAL MODELLING

Mathematical modelling aims to optimise the energy consumption of a system by define it as a function of its working parameters. Response Surface Method (RSM) was used by Draganescu for this purpose, where number of experiments and iterations under different conditions for the same process, machines or lines were performed before processing the collected energy data mathematically, and finally the energy data were linked to the process parameters [35]. Although RSM can give good results in term of reducing energy consumption, it does not consider any physics involved to ease the modelling process. Hence, the terms appearing in such models have no physical meanings which limits any further investigation about system efficiency.

Jin outlines a mathematical model that can compute an environmental impact score for each machining operation based on the environmental impact of the materials used based on commercial database tools like ECO-SCAN [49]. However, it provides only vague score for environmentally impact that tells nothing about energy consumption.

Statistical discrete event formulation was used by Dietmar with simple measurements to define parameter data needed to characterise discrete events [34]. This effort led to the present a generic approach to model energy consumption of a machine.

2.9.5 STATE-TRANSITION MODELLING

Action-Oriented, Event-Driven, Task-Oriented modelling are other names in the literature for this modelling technique. It originates from the fact that the energy consumption of a system is strongly connected to its operating states [22], in other words energy consumption is dynamically depends on tasks variability within the manufacturing system.

Each type of production equipment has its own various operating states such as switch on/off, warm up, processing, idle, stand by, etc. and each of these states has its own energy consumption, some of them consumes fixed amount of energy like stand-by state, and some of them consumes variable amount of energy like processing state. Specific energy consumption per each production operation is independent of the nature of specific production task. Thus, every production operation can be described as a chain of operating states and their corresponding energy. Moreover, any set of state chains from either manufactured product or used equipment perspectives can be modelled and give the decision maker various operation alternatives for the desired manufacturing task. It is important to assign the equipment that will execute each process at scheduling phase as it has an influence on the resulted estimation of the required energy. Consequently, decisions like machine energy levelling and peaks capping can then be taken robustly [88].

Since this method formulates the consumed energy behaviour of the whole operation by considering the energy consumption at each individual operating state or event, it is considered to be generic, scalable to the system size and details required, considers how the system is being used, and needs small computational capabilities [33].

The State-Transition modelling method has been used in this research because of its obvious physical meaning, and practically to enable the energy optimisation. Using this method, every operation can be described as a chain of operating states with integrated energy profiles as illustrated in the Chapter 3.

2.10 SUMMARY

On one hand, the academics have conducted a wide range of research areas under the umbrella of sustainable manufacturing; from introducing carbon emission signature of an individual manufactured part, to identifying the impacts of alternative machining strategies in numerically controlled (NC) machines on their energy consumption [17], and suggesting metrics to measure sustainability performance throughout system lifecycle and process development [74]. In fact, the methods that have been suggested so far deal with the targeted systems (components, machines or lines) as black boxes; as the energy consumption modelling carried out by measurements and experiments [22].

On the other hand, the current energy management practices in industry have been highlighted and discussed, and their shortfalls have been addressed. It is worth noting that typically machine builders and system integrators do not include accurate energy consumption data in manufacturing system to enable manufacturers to manage the operational costs and environmental performance. This is mainly due to the fact that there is no robust tool available in the market which can predict the energy consumption at the design phase, and examine different alternatives.

Research works on the energy optimisation of manufacturing machines have investigated the impacts of idle times, velocity profiles and mechanisms paths on the consumed energy. It is noted that these optimisation methods are non-coupled, and most of the time, been used individually. Therefore, these optimisation methods could be effective if they are integrated in one framework, and implemented throughout the lifecycle of manufacturing systems.

CHAPTER 3

METHODOLOGY & IMPLEMENTATION

3.1 INTRODUCTION

The literature review in Chapter 2 has stressed the importance of energy prediction throughout the manufacturing system lifecycle, especially at the design phase. It has also highlighted the efforts that have been invested in order to predict energy consumption in manufacturing operations. These efforts mainly aim at more energy-efficient operations and ultimately more sustainable manufacturing. However, the amount of energy that can be saved by implementing the current reactive practices can be maximised by implementing proactive practices for the reasons that will be detailed in this chapter.

The gap between what is needed to improve the energy efficiency of manufacturing systems, and what is offered by current practices has been identified in this work of research. Based on that, the author believes that the realisation of a proactive, holistic and readily applicable framework for energy prediction is a crucially needed step towards better energy optimisation, and consequently more environment-friendly manufacturing.

However, most of the available Virtual Engineering (VE) tools, which are heavily used throughout the lifecycle phases of manufacturing systems, do not provide the sufficient energy-related information that is necessary to predict and optimise their energy consumption. The reason behind this is that these VE tools are principally designed to perform their modelling, simulation and validation functions without taking into their account the environmental consequences.

Furthermore, the available energy modelling tools either require hard to attain information, or the developed models at the design phase cannot be further used at later phases of the system lifecycle. Also, it is often the case that none but one of all the energy optimisation methods is considered and implemented; that is 'idle time optimisation'. Consequently, these tools and methods are not adopted in industry because of their lack of supporting the functional requirements.

Therefore, this chapter, first, proposes the novel CBEO framework that addresses the aforementioned limitations and aims to provide a comprehensive and applicable solution for more energy saving at machine level. Second, the methodology and implementation of the proposed CBEO framework are presented. This is followed by critically reviewing the existing vueOne VE toolset and discussing the required enhancements to its data structure and optimisation parameters. Finally, the proposed structure of the Energy Optimiser software is also presented.

3.2 SYSTEM ENERGY OPTIMISATION REQUIREMENTS

It is of high relevance to this section to note that this research has been funded by EPSRC via CASE program. Ford Motors Company UK has been a main contributor, hence they were actively involved in defining the user requirements[1].

The purpose of this section is to highlight the end-user requirements and specifications of the CBEO framework outputs to be applied and implemented. These requirements are important to ensure best practice and to promote operation energy efficiency.

- **Machine cycle time:** It was stated that machine cycle time should not be changed, thus the proposed reconfiguration to achieve the energy optimisation should be implemented within the same cycle time. This is due to two main reasons: first, the scope of this research is the standalone machine level; there are other works of ongoing research focusing on the production line level. Second, the production line that contains these machines is assumed to be balanced.

- **Electrical and pneumatic components:** Electrical and pneumatic actuators are widely used in assembly systems. This is accompanied by inefficient energy consumption by these actuators. In order for the energy usage of motors and air compressors, operating different actuators, to be optimised, the amount of this energy usage has to be predicted.

- **Drive losses:** Most of actuators require drives or controllers for control purposes. These drives require energy to power their electronics and operate the attached motors and compressors. These energy losses, which determine the drive efficiency, are dissipated as heat during the idle and operation states of actuators. Drives energy consumption should be modelled in order to predict component and system consumption accurately.

[1] The important role of automotive manufacturers in improving the sustainable manufacturing is mentioned in section 1.1. Also, ASG's main objective, as mentioned in section 1.4, is to develop manufacturing approaches and tools to improve manufacturing activities in automotive industry.

- **Modes of operation:** During machine cycle time, its actuator components stay idle for some time because they are waiting for their turn to perform their tasks, or they have already completed these tasks. High amount of energy can be saved by switching these idle components into the sleep or off modes instead of the inefficient idle mode. During the sleep mode, the actuator (motor, compressor, pump, etc.) is turned off while its drive stays on, whereas during off mode both the actuator and its attached drive are switched off waiting for the system controller signal to start again. In order to achieve this, software and/or hardware changes on the manufacturing machine are required.

- **Peak energy:** During manufacturing system operation, several components may start at the same time, leading to high energy demands and power peaks at these specific times. In addition to the associated additional energy cost caused by these peaks, fines are applied by energy suppliers, and technical malfunctions may occur either immediately or in time. This undesired situation can be avoided by introducing kind of interlock or offset between system components to ensure only one component starts at a given time, which can be done by adding on-delay timers to the PLC program, or even changing the sequence of operation of a manufacturing machine.

- **Machine trajectory:** The sequence of operation of different components during a machine operation cycle determines its trajectory. Different trajectories have different energy consumption. Alternative trajectories must be validated virtually before selecting the most energy efficient trajectory.

- **Smooth moves:** Applying the proposed optimisation methods should be accompanied by smooth, jerk limited, and minimised vibration moves because these behaviours have bad impacts on the mechanical parts of the manufacturing machines as well as their energy consumption. Controlling the smoothness of each actuator’s moves is mainly achieved by limiting their jerk, which can be done by optimising their velocity profiles. Altering velocity profiles requires software changes on the drive settings in most cases, and in some cases the drive does not support smoother and more energy efficient motion profiles which requires replacing it with a better performance drive.

- **Performance and safety:** Finally, any energy optimisation activity on manufacturing machines must not compromise or degrade their performance and safety. Exposing human operators to dangers is strictly prohibited. Also, the mechanical and electronic parts must not be at risk.

3.3 THE PROPOSED PROACTIVE STRATEGY BASED ON INTERNAL-MODEL-BASED CONTROL THEORY

As stated earlier in the literature review, decision makers in manufacturing firms are incentivised by the governmental regulations to operate production facilities taking in account certain energy consumption thresholds that are not to be exceeded. The existing energy monitoring practices are important to give a clear picture and ensure that these activities at the operation phase are performed efficiently. However, there is still an urgent need for a proactive and holistic framework to bridge the shortfall of the current reactive practices, as mentioned in section 1.2. This research seeks to develop such framework.

Analysing the proposed proactive framework against the current reactive industrial practices according to control systems theories is expected to lead to an improved understanding, and gives this framework a solid foundation based on an established theory.

Figures 3.1 and 3.2 depict the current energy monitoring practice at the operation phase, and the proposed energy prediction procedure at the design phase, respectively, using control systems terms and concepts.

The blocks shown in the block diagrams of figures 3.1 and 3.2 represent the sub-systems that form the control process of a manufacturing system energy consumption, and the connected arrows represent the transformed variables. The sub-systems are valid provided they are: linear and each of them does not load the preceding one(s).

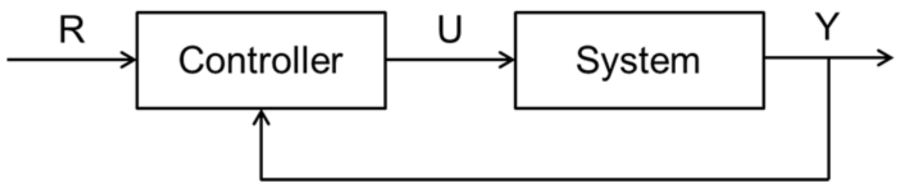


Figure 3.1: Current energy monitoring practice at system operation phase based on basic feedback theory

From Figure 1, the *System* represents the already built manufacturing machine for which the energy consumption is to be monitored. *Y* is the energy consumed by the *System* at its operation phase, and it is monitored. *R* is the limit, threshold or reference energy consumption. The *Controller* (decision maker or software) is fed by *R* and *Y*, and according to some rules and restrictions it provides the actuating action *U* to operate the *System* accordingly.

By defining *System's* configurations, settings and sequences, the action *U* solely determines *System* energy consumption. Thus, action *U* should be generated to enable the *System* to consume the optimal amount of energy. However, it is not possible with this error driven yet dominant reactive practice shown in Figure 3.1. Therefore, this passive or reactive practice, which is fundamentally based on correcting the faults or the undesired results that have already occurred, has to be promoted.

The current feedback practice forms the skeleton for the development of the proposed proactive framework that has the potential to achieve the best possible energy consumption, by optimising the action *U*.

The proposed proactive energy prediction procedure to generate the action *U* at the *System* design phase, and throughout its lifecycle, is based on the Internal-Model-Based Control (IMC) theory [83]. The IMC block diagram is shown in Figure 3.2.

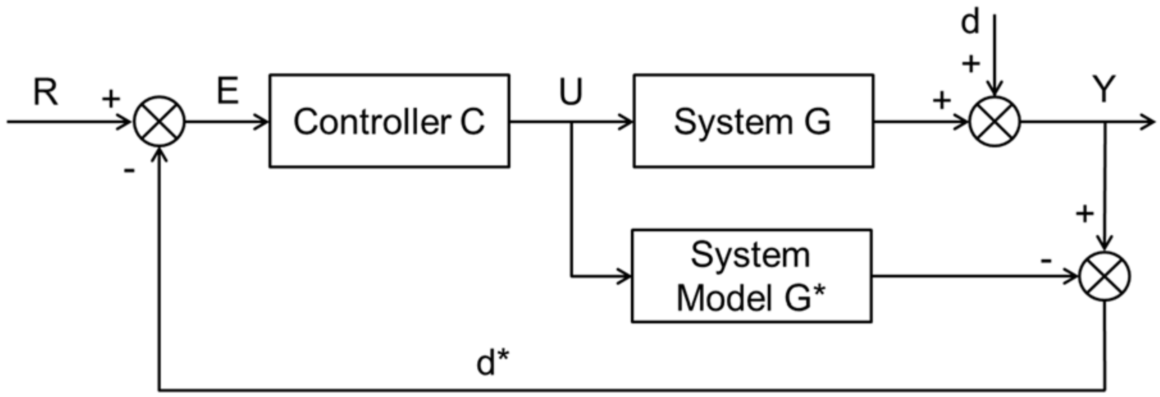


Figure 3.2: The proposed energy prediction procedure at the system design phase based on the IMC theory [83]

The proposed proactive procedure is considered by the author to be the reasonable successor of the current passive practice that is emulated in Figure 3.1. It is worth noting that there can be different control procedures, exploiting different control theories, to achieve optimal action *U* [31]. These procedures are expected to lead to fairly accurate energy prediction at the *System* design phase, which in turn can be used to optimise the actual energy consumption at its operation phase. Applying IMC theory is expected to give the required solid foundation of the proposed Component-Based Energy Optimisation (CBEO) framework, which aims to eliminate the causes that lead to the undesired actual values of *System* energy consumption *Y* at the operation phase, rather than passively reacting to it later at the operation phase as the current industrial practices and tools do.

The IMC philosophy states that if any system contains within it, implicitly or explicitly, some representation of the process to be controlled then a perfect control is achievable [83]. In particular, if the *Controller C* has been developed based on the exact model, *System Model G*,* of the *System G* to be controlled, then perfect and proactive prediction is theoretically possible. In practice, a mismatch between the *System G* and its *System Model G** is often common due to external disturbances and/or internal parameter variations. Therefore, to predict the energy consumption of *System G* early at the design phase, this energy consumption should be modelled within its virtual *System Model G**. However, a feedback closed-loop is necessary since it is expected that the knowledge about *System* energy consumption is often inaccurate or incomplete.

In Figure 3.2, *d* is an unknown disturbance that could affect *System G*, hence its energy consumption. It could be internal disturbance such as wear or aging issues with a component, or external disturbance such as excessive environmental conditions or unexpected increase of work load. *U* is the action taken by the *Controller C* to make *System G* performs its functions yet consumes the optimised amount of energy. *U* is introduced to both the *System G* and its *System Model G**. *Y* is the actual energy consumption by *System G,* which is then to be compared with the predicted energy of *System Model G**, resulting in $d*$ as a difference between the actual and predicted energy consumption. That is

$$d^* = (G - G^*)U + d$$

If $G = G^*$ which can be achieved by exact modelling, then d^* is equal to the unknown disturbance *d*. On the other hand, if the *System G* works in normal operating conditions and no presence of any disturbance is observed, then *d* becomes zero, meaning d^* is a measure of energy consumption discrepancies between the *System G* and its *System Model G**. Thus, d^* may be considered as the energy information that is missing in the virtual *System Model G**, and can therefore be used to improve controlling the actual energy to be consumed by the real *System G*. This can be done by subtracting d^* from reference energy threshold, *R*. The resulting action *U* is given by

$$U = (R - d^*)C = (R - (G - G^*)U - d)C$$

Thus,

$$U = \frac{(R-d)C}{1+(G-G^*)C}$$

Since $Y = (G * U) + d$, the closed-loop transfer function from the IMC scheme is therefore

$$Y = \frac{(R-d)CG}{1+(G-G^*)C} + d$$

or

$$Y = \frac{CGR + (1-CG^*)d}{1+(G-G^*)C}$$

From the last equation, it can be seen that if $C = 1 / G^*$ (the *Controller C* has been developed based on the inverse of the *System Model G*. The *Controller C* is the energy prediction procedure that includes implicitly the required energy data of the *System G* from its modelled *System Model G**), and if $G = G^*$ (no mismatch between the real *System G* and its developed virtual *System Model G**), then $Y = R$, meaning perfect reference or threshold *R* targeting, and disturbance *d* eliminating are proactively achieved. It is worth noting that, even if $G \neq G^*$, perfect disturbance *d* eliminating can still be achieved provided $C = 1 / G^*$ [48].

Consequently, the optimisation methods applied to *System Model G** at the design phase, are expected to achieve the optimal energy consumption at the *System G* operation phase. Thus, the aim of this research, to proactively predict and optimise the energy consumption of a manufacturing system, is achieved.

In this section, the difference between the current reactive industrial practices, and the proposed novel proactive practices towards more energy efficient activities has been highlighted. In the next subsection, the conceptual workflow of the proposed CBEO framework is explained.

3.3.1 WORKFLOW OF THE PROPSED CBEO FRAMEWORK

The CBEO framework is proposed to integrate the currently non-coupled energy modelling and optimisation methods within a component-based VE tool. This is based on the established IMC theory equipped with the current energy management techniques in order to ensure the best achievable energy saving, even in the absence of ideal operating conditions and accurate energy modelling.

Figure 3.3 shows the conceptual workflow of the proposed CBEO framework. Its realisation within the VE vueOne tool is highlighted in section 1.4. The rest of this chapter explains the implementation of the CBEO framework, and its Energy Optimiser tool that has been developed by the author.

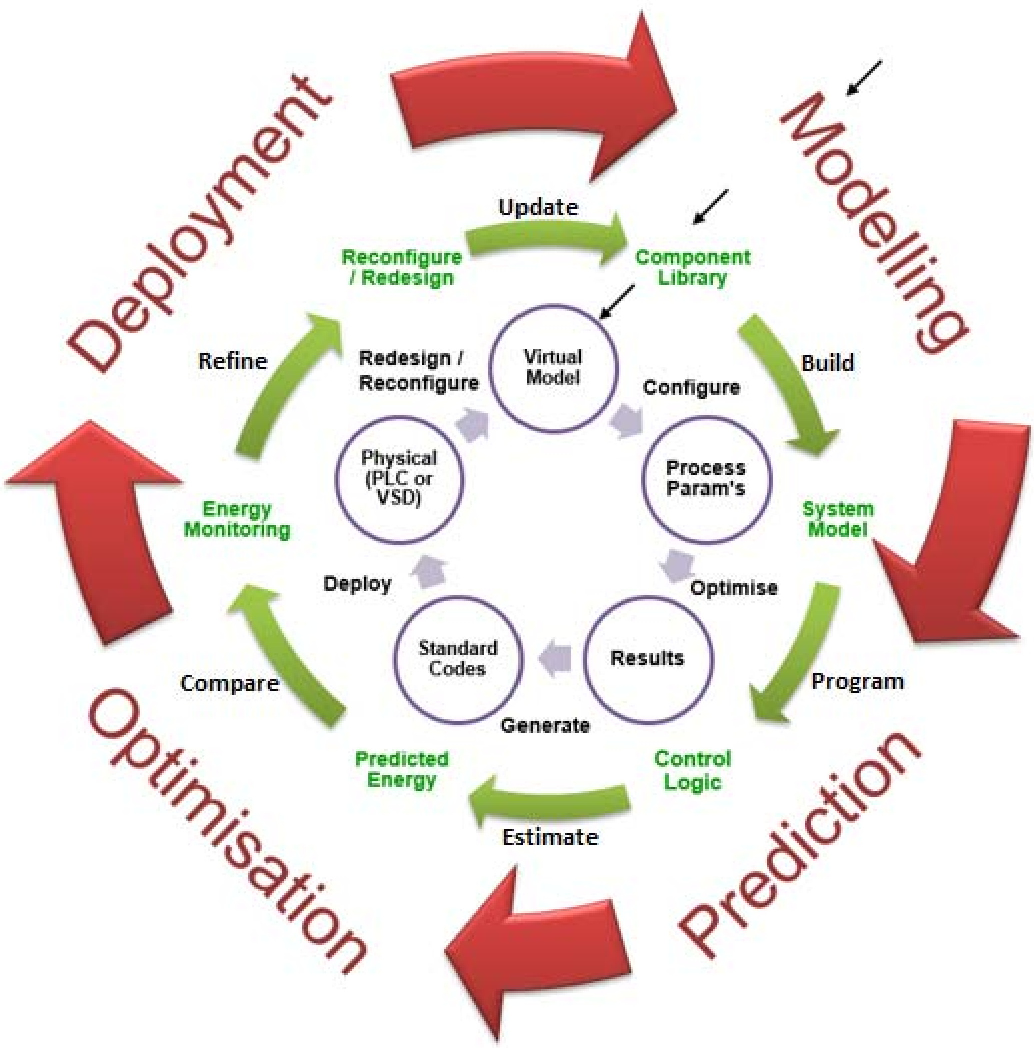


Figure 3.3: The conceptual workflow of the CBEO framework.

The black arrows shown in the figure indicate where the framework typically starts its optimisation process. The outer red circle gives a very conceptual overview of the CBEO framework functions, whereas the two inner circles show the detailed capabilities that are expected to be achieved by implementing it as explained in the rest of this sub-section.

Using the CBEO framework, deploying achievable energy efficient design of an assembly machine is facilitated. Alternative machine designs are optimised then the selected design is virtually validated and then deployed to the physically built machine. However, within each modelled component, the required energy related information must be available in order to predict then optimise effectively the energy consumption of the targeted manufacturing machine.

The inclusion of energy consumption data at the component level is expected to enable the proactive prediction and optimisation of the energy consumption at the machine level throughout its lifecycle, particularly at the design phase where most benefit can be attained in terms of minimising time, cost, disruption and risk.

The State-Transition modelling method, which has been mentioned in section 2.9.5, has been used in this research to facilitate the energy prediction. Using this method, every operation of every component can be described as a chain of operating states with integrated energy profiles. The aggregate sum of the consumed energy of the participating components during different operating states is the overall consumption of the given manufacturing machine.

Since this modelling method formulates the consumed energy behaviour of the whole operation by taking into account the energy consumption at each individual operating state or event, it is considered to be generic, scalable to the system size and details required, representing how the system is being used, and requiring less computational capabilities [33].

The machine virtual model can be created by assembling verified off-the-shelf library components that are reusable and reconfigurable in terms of their physical attributes, kinematics, control and operational behaviour. The resulted machine model is then simulated and validated to predict the amount of energy that will be consumed at the operation phase. Proposing alternative designs and components configurations, according to different energy optimisation methods, is available throughout the machine lifecycle.

Different methods of optimising individual components and the whole machines from energy consumption point of view can be applied. These methods are presented later in section 3.5. Considering system hardware and software capabilities, the optimised configurations and control methods can be deployed to real systems. Typically, automated deployment methods over communication networks with the real system controllers are cost and time effective compared to conventional deployment methods, where design engineers are required to carry out the control deployment manually in the presence of physical hardware.

Once the virtual model is optimised, in accordance with the updated components, the runtime control code for system controllers is then ready to be generated and downloaded to target controllers. Therefore, the system will perform its functions in an energy efficient manner during its operation phase.

In case of already established machines, the actual energy measurements of the consumed energy by individual components and whole machines are important for tuning and refinement purposes. Furthermore, automated capturing of the real energy data during the operation phase is expected to make the created virtual model more consistent with the physical system in the context of energy consumption.

Therefore, the component library should be always updated with the closest representation of the consumed energy by the real components. This refinement process makes the components, residing in the component library, more reliable to be reused at any phase of the machine lifecycle, and enables reliable system reconfiguration and redesign alternatives.

Further implementation of the proposed predictive energy optimisation framework within the conventional feedback energy monitoring practice is expected to provide an innovative solution for the energy optimisation of assembly systems. This, in turn, will enable manufacturing firms to have better control of the running costs and the environmental burdens associated with the manufacturing activities.

3.4 ENERGY PREDICTION PROCEDURE

3.4.1 COMPONENT ENERGY MODELLING

The energy consumption of a component is either constant or variable over its operating time. The constant energy is consumed by *Base* components that are needed to enable the system to perform its operation (e.g. cooling fan, HMI screen, etc.). On the other hand, variable amount of energy is consumed by components that operate with respect to their parameters (kinematics and dynamics behaviours) and operational state (control behaviour) [22]. The classification of components based on their energy consumption is shown in figure 3.4 below. It is worth noting that many components may consume some energy whilst idle because of their drives' losses [14].

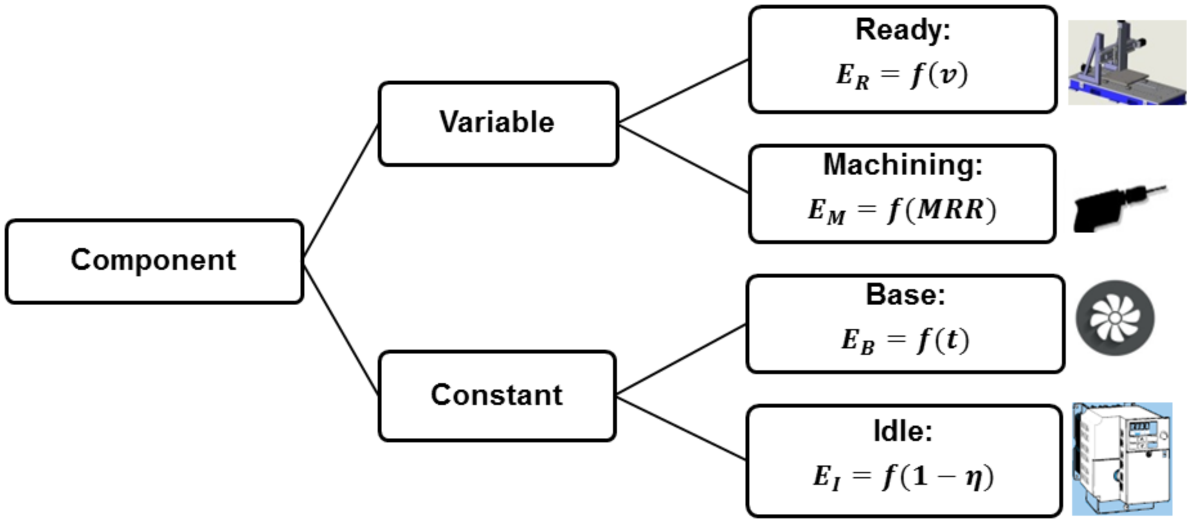


Figure 3.4: Components classification in terms of their energy consumption.

- *Base* energy components: consume constant amount of energy over the system operating time t (examples of such consumers are: lubrication pump, coolant pump, PLC power supply, etc.).
- *Idle* energy losses: represent the energy losses by each component (*Base*, *Ready* or *Machining*) at its idle state (these losses are implicitly included in a component energy model during its operating state). These energy losses are function of the drive efficiency η, which is constant.

Variable energy consumers are classified into two groups [18]:

- *Ready* energy components: represent moving-only components which transport tools and work-pieces to carry out machining/assembly tasks (such as gantries). The energy consumption of such components is mainly a function of their velocity v [64].
- *Machining* energy components: represent components which perform actual machining (such as drills, etc.). The energy consumption of such components is mainly a function of Material Removal Rate (MRR) [32, 57]

The equation below represents the total energy consumption of a modelled system depending on operating conditions (idle, operating, stand-by or off) of each one of its components

$$E_{tot} = \sum_{n_0}^{n} E_{con,n} + \sum_{m_0}^{m} E_{var,m}$$

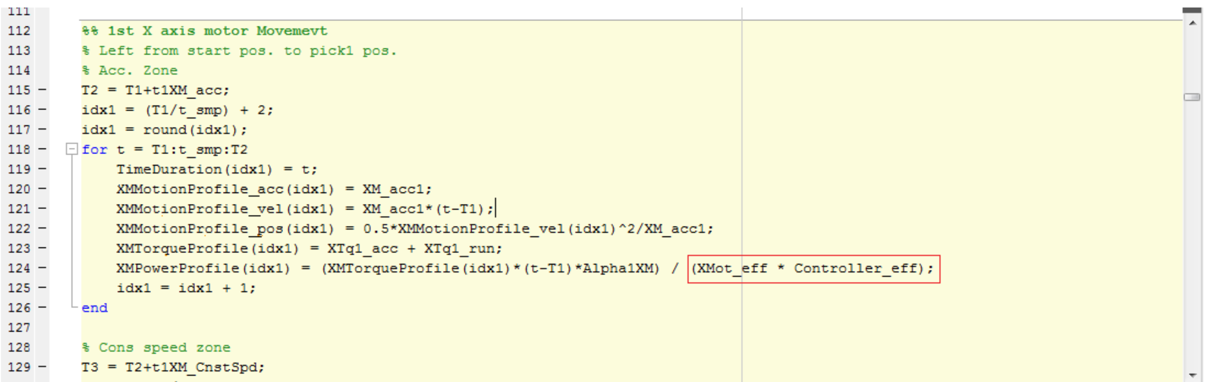
where; E_{tot} is the total consumed energy in kilowatt hour (KWh) by the system under investigation,

$E_{con,n}$ is the consumed constant energy in KWh by *Base* energy components $n_o - n$ and Idle losses, and

$E_{var,m}$ is the consumed variable energy by variable (*Ready* and *Machining*) energy components $m_o - m$.

It is worth noting that *Machining* components' actual energy consumption is typically only 15-35% of the whole consumed energy by machines during their machining (milling, turning, cutting, etc.) processes, while the rest is consumed by both constant (*Base* and *Idle*) and *Ready* components [38, 41, 33].

Figure 3.5 shows a screenshot that was taken from the Matlab code of the developed Energy Optimiser tool as an outcome of this research. The figure shows the modelled energy consumption of the X axis (representing a *Ready* consumer) during its acceleration time to move from its start position to its first lid pick position (detailed explanation about these operations is available in Chapter 4), considering its motor and drive energy losses.



```
%% 1st X axis motor Movemevt
% Left from start pos. to pick1 pos.
% Acc. Zone
T2 = T1+t1XM_acc;
idx1 = (T1/t_smp) + 2;
idx1 = round(idx1);
for t = T1:t_smp:T2
    TimeDuration(idx1) = t;
    XMMotionProfile_acc(idx1) = XM_acc1;
    XMMotionProfile_vel(idx1) = XM_acc1*(t-T1);
    XMMotionProfile_pos(idx1) = 0.5*XMMotionProfile_vel(idx1)^2/XM_acc1;
    XMTorqueProfile(idx1) = XTq1_acc + XTq1_run;
    XMPowerProfile(idx1) = (XMTorqueProfile(idx1)*(t-T1)*Alpha1XM) / (XMot_eff * Controller_eff);
    idx1 = idx1 + 1;
end

% Cons speed zone
T3 = T2+t1XM_CnstSpd;
```

Figure 3.5: Modelling *Ready* component considering its drive and motor losses

3.4.1.1 Modelling *Variable* Component Energy Consumption

The scope of this research is to predict and optimise the energy consumption of assembly systems, where no *Machining* components take part in the assembly operations. Thus, we present only the *Ready* components and leave the *Machining* components to be investigated further as a future direction of this research.

There are many different mechanisms that are typically used in the assembly applications. In this research, five main assembly mechanisms have been considered to represent the *Ready* components energy consumption. In general, other mechanisms can be approximated to one of these five mechanisms. Each mechanism has its own torque and inertia formulas based on its physical specifications. However, the following formulas are common between all of them:

$$Energy = \int_{t_0}^{t} Power \, . \, dt$$

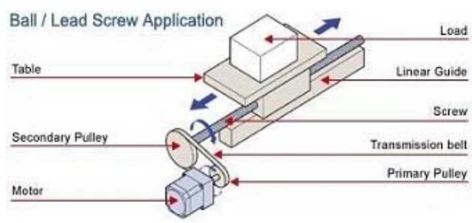
$$Power = (Trq_{acc} + Trq_{run}) * Velocity_{angular}$$

$$Force_{Tot} = Force_{Friction} + Force_{gravity} + Force_{external}$$

$$Trq_{acc} = Inertia_{Tot} * Acceleration_{angular}$$

The considered main mechanisms are: 1) ball or lead screw, 2) belt conveyor or gantry, 3) rack and pinion, 4) index table, and 5) swivel arm.

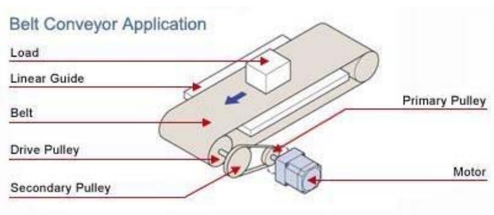
- **Ball or lead screw:**



$$Trq_{run} = Force_{Tot} * (\frac{lead}{2 * \pi * Eff_{screw}})/Ratio_{Trns}$$

$$\begin{aligned} Inertia_{Tot} = {} & Inertia_{motor} + Inertia_{gear/belt} \\ & + (Inertia_{screw} + Inertia_{load} \\ & + Inertia_{coupling} \\ & + Inertia_{Table})/Ratio^2_{Trns} \end{aligned}$$

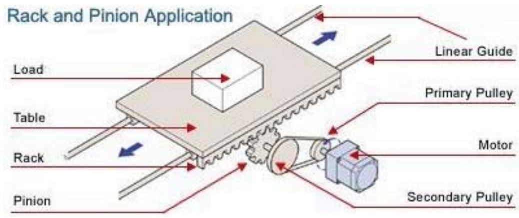
- **Belt conveyour or gantry:**



$$Trq_{run} = Force_{Tot} * Radius_{DrivePulley}/Ratio_{Trns}$$

$$\begin{aligned} Inertia_{Tot} = {} & Inertia_{motor} + Inertia_{gear/belt} \\ & + (Inertia_{Belt} + Inertia_{load} \\ & + Inertia_{coupling} + Inertia_{Pull\_P} \\ & + Inertia_{Pull\_S})/Ratio^2_{Trns} \end{aligned}$$

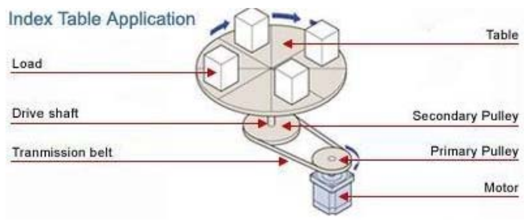
- **Rack and pinion:**



$$Trq_{run} = Force_{Tot} * Radius_{Pinion}/Ratio_{Trns}$$

$$\begin{aligned} Inertia_{Tot} = {} & Inertia_{motor} + Inertia_{gear/belt} \\ & + (Inertia_{Rack} + Inertia_{load} \\ & + Inertia_{coupling} + Inertia_{Table} \\ & + Inertia_{Pinion})/Ratio^2_{Trns} \end{aligned}$$

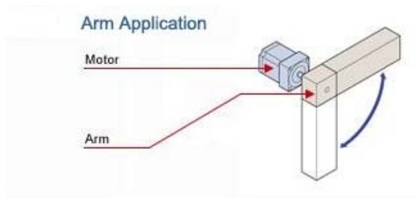
- **Index table:**



$$Trq_{run} = Force_{Tot} * \frac{Distance_{GrvtyCntrToRotCntr}}{Ratio_{Trns}}$$

$$\begin{aligned} Inertia_{Tot} = {} & Inertia_{motor} + Inertia_{gear/belt} \\ & + (Inertia_{Shaft} + Inertia_{load} \\ & + Inertia_{coupling} + Inertia_{Pull\_P} \\ & + Inertia_{Pull\_S})/Ratio^2_{Trns} \end{aligned}$$

- **Swivel Arm:**



$$Trq_{run} = Force_{Tot} * \frac{Distance_{GrvtyCntrToRotCntr}}{Ratio_{Trns}}$$

$$\begin{aligned} Inertia_{Tot} = {} & Inertia_{motor} + Inertia_{gear/belt} + (Inertia_{load} + Inertia_{coupling} \\ & + Inertia_{Arm})/Ratio^2_{Trns} \end{aligned}$$

3.4.1.2*Constant* Components Energy Consumption

The *Base* energy consumers stay operating at a constant pace over the machine operating time, hence consume their rated energy over this time. Therefore, a constant figure that is taken from the *Base* component data sheet is sufficient to model this type of components.

On the other hand, if a machine stops waiting to perform its next cycle, then there are two different possible scenarios to describe the *Base* energy consumption, the common between them is that in both cases a data sheet constant figure represents the energy consumption as explained below:

- the component has a drive to reduce its speed by a specific percentage of its rated power/energy,
- the *Base* component has no drive, then the consumed energy will be its rated energy.

Idle losses must be included in the energy prediction process, since they represent consumers' (*Base*, *Ready* and *Machining*) losses while they are idle, yet their drives still consume energy. This energy is required to power up the drives' electronics, and/or keep the motors energised and ready to operate. Examples are:

- The *Base* component has a drive to switch it into a sleep (or stand-by) mode to save energy while the machine is waiting to start its next cycle. Thus, the amount of consumed energy is the energy required to power up the drive electronics (constant amount of energy given in the drive datasheet)
- During system operation, one or more *Ready* or *Machining* components have completed their moves and waiting for the next ones, but their controllers keep their motors energised. Thus, the amount of energy consumed in this case for each component is its controller losses, and its motor rated energy consumption.

3.4.2 MODELING VERIFICATION

The energy modelling verification process is shown in figure 3.6. Modelling verification should be a continuous operation, to ensure the most updated information about components in real world is represented in their virtual models.

Initial verification is required for each newly modelled component before adding it into the Component Library, in order to make sure the modelled energy trace is within a reasonable tolerance limit of the actual consumption. This tolerance between real and predicted energy consumption by each component should be minimised as long as the library is updated, and the component energy tuning is carried out. Therefore, actual measurements need to be performed at physical components for calibration and validation purposes.

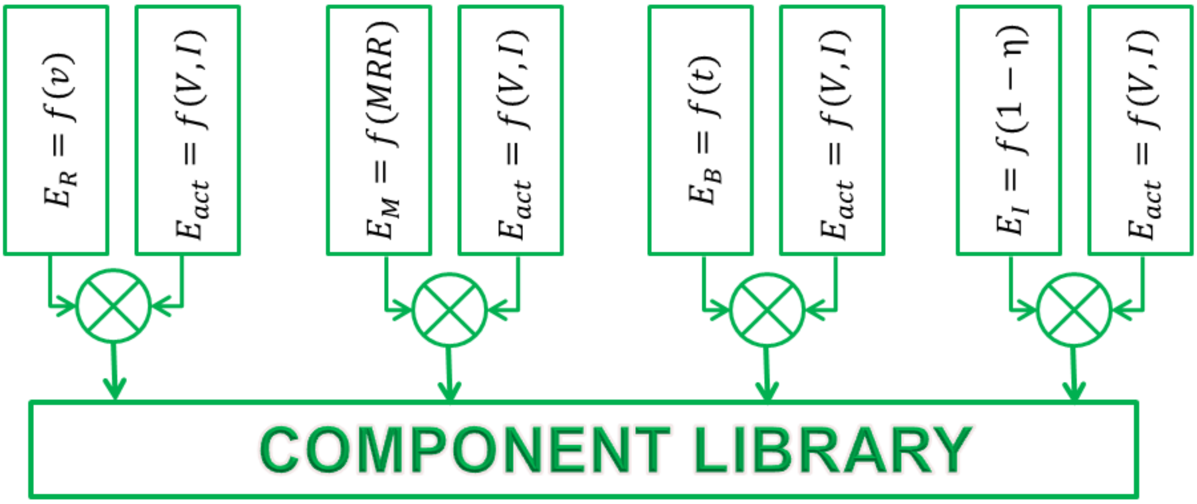


Figure 3.6: Energy modelling verification process.

For electric driven components, actual energy consumption (E_{act}, which is a function of the applied root-mean-square (RMS) voltage V_{RMS}, and the drawn current I_{RMS}) by each modelled component (E_B consumed by the *Base* component, E_R consumed by the *Ready* component, E_M consumed by the *Machining* component, and E_I consumed by any component while idle) needs to be measured under normal operation conditions.

Analysis and comparisons between the actual and the modelled values need to be undertaken to ensure that the modelling process is accurate before initially storing the energy component models in the virtual Component Library. Then, they can be (re)used to design build bigger machines, which energy consumption can be accurately predicted at the operation phase.

In the case of already established machine that is under optimisation investigation at its operation phase, several factors (e.g. components oversizing, wear, aging, heat dissipation, etc.) can result in discrepancies between the measured and the predicted energy consumption. Thus, design engineers need to take these factors into account in order to compensate for these discrepancies and tune the VE data set and model. For example, if the measured consumption of a component keeps showing almost the same offset against the predicted consumption because of any of the aforementioned reasons, then a multiplication factor should be applied to unify these results and update the energy model in the Library.

Chapter 4 shows in details the modelling verification process for different components installed in a physical assembly machine. It can be observed that the regular offset between measured and predicted consumption, and how this issue is addressed as a part of the verification process.

3.5 ENERGY OPTIMISATION METHODS

Once the component energy is accurately predicted at the machine design phase, and its energy consumption model is verified and refined based on the operation phase measurements, then the energy optimisation at the component and machine levels can be performed from two perspectives; Component Optimisation (CO) and Sequence of Operation Optimisation (SOO). Both CO and SOO can be conducted independently, however optimum energy saving requires optimisation of the energy model at both component and machine levels.

3.5.1 COMPONENT OPTIMISATION (CO)

Components can be optimised based on their type (i.e. *Base*, *Ready* or *Machining*), two optimisation methods are presented: acceleration optimisation, and operation modes optimisation as follows.

3.5.1.1 Acceleration Optimisation

The *Ready* energy consumers can be optimised by changing their velocity profiles i.e. the acceleration and deceleration values, which in turn regulate the required torque to be developed by the actuator to achieve the desired moves. As explained in sub-section 3.4.1.1, the energy consumption of the *Ready* components depends on the required torque to be developed by these components.

The motion of the moving *Ready* components can be defined by determining its velocity profile. The velocity profile in turn is defined by four properties: acceleration, speed, distance and time. Different velocity profiles and acceleration / deceleration values can be determined by using the well-known Equations of Motion.

Considering the trapezoidal velocity profile that is shown in figure 3.7, if the distance to be covered while the actuator is accelerating and decelerating are equals, and each of them is one fourth of the total distance X. And if the times for accelerating, decelerating and moving the load in a constant speed are equals and their sum equals the total move time S then:

$$acc\ (a) = -dec\ (d) = \frac{2 * distace}{time^2} = \frac{2 * \left(\frac{X}{4}\right)}{\left(\frac{S}{3}\right)^2} = \frac{4.5 * X}{S^2}$$

And

$$vel\ (v) = acc * time = \frac{4.5 * X}{S^2} * \frac{S}{3} = \frac{1.5 * X}{S}$$

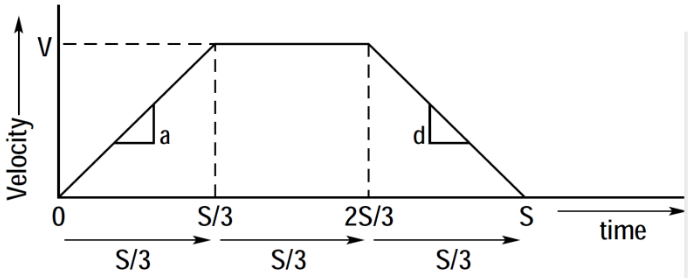


Figure 3.7: The trapezoidal velocity profile

Changing the values of the acceleration / deceleration time and distances will change the values of the acceleration and the velocity in the same manner as explained in the above equations. If the acceleration and deceleration times are equal and the sum of them is the total move time, and same with the distance, then a triangular profile is emerged leaving no chance for the actuator to move in a constant velocity. Therefore, the acceleration value $a = -d = \frac{4*X}{S^2}$, and the maximum velocity value $v_{max} = \frac{2*X}{S}$.

Hence, changing the acceleration time relative to the total move time and, the acceleration distance relative to the total distance results different shapes of the trapezoidal and the triangular profiles, with different values of the acceleration, deceleration and velocity. Thus, the consumed energy by the component to perform each move is also changed.

In the aforementioned trapezoidal velocity profile, the value of the acceleration is constant over the acceleration time, because it is the derivative of the straight velocity line. Thus, if the velocity profile takes more curvy shape over the same acceleration time, then the acceleration value will be a function which its average value is less than the constant value in trapezoidal velocity profile. Given that, the energy consumption of the moving actuator is proportional to its acceleration value of each move, therefore, configuring the actuator moves to follow the s-curve profile is expected to promote component energy efficiency.

However, forming the s-curve velocity profile is more complicated than the trapezoidal velocity profiles, since an additional jerk property is required to be defined. This makes the equations more non-linear. Figure 3.8 shows the difference between these two profiles.

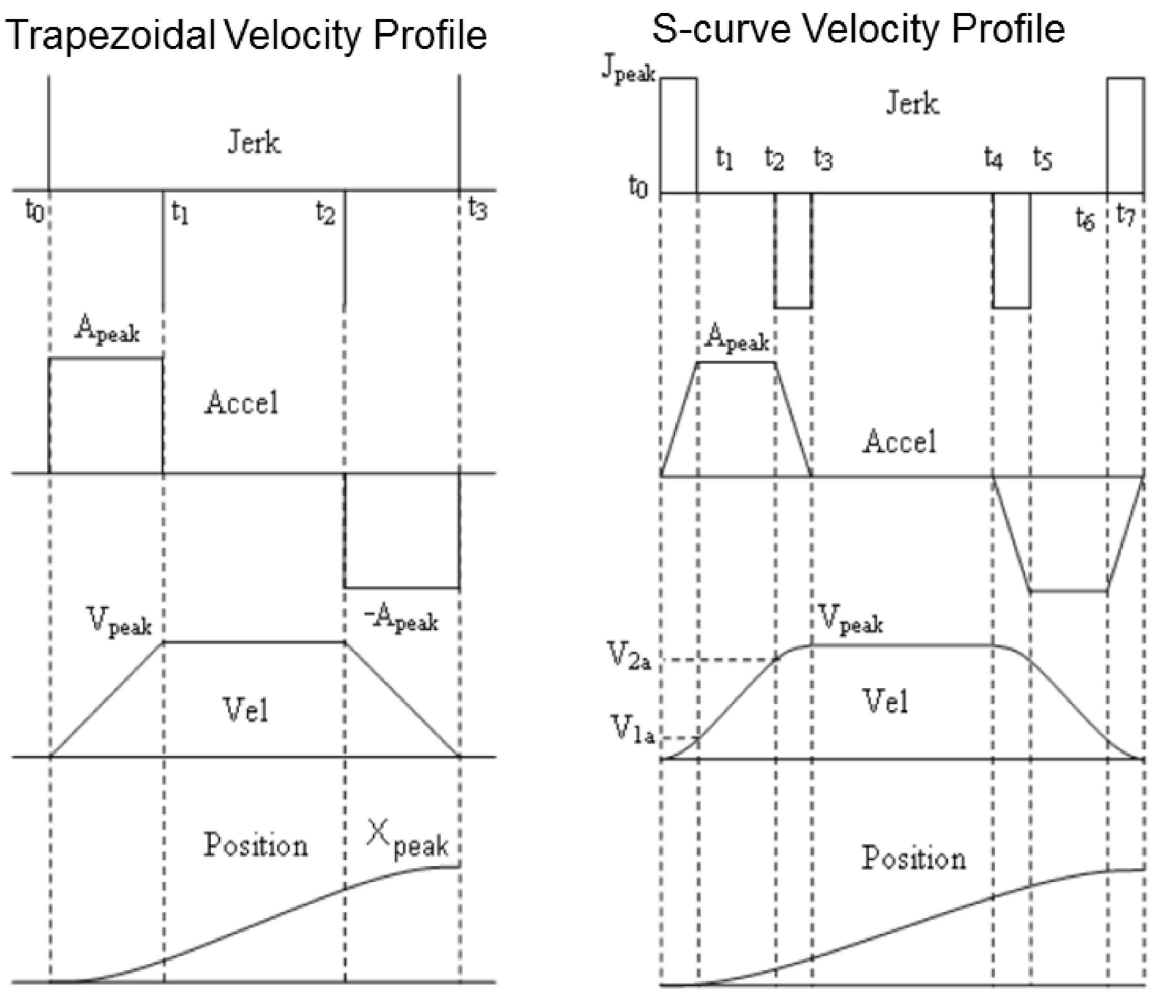


Figure 3.8: The trapezoidal and s-curve velocity motion profiles

In the trapezoidal velocity profile, each move consists of three distinguished segments: acceleration, constant velocity and deceleration, whereas s-curve segments are: acceleration ramp up, constant acceleration, acceleration ramp down, constant velocity, deceleration ramp up, constant deceleration and deceleration ramp down. It is worth mentioning that the jerk is theoretically unlimited in the trapezoidal and the triangular velocity profile whereas it is limited in s-curve velocity profile. Thus, the s-curve moves are smoother and causes less vibration in the real applications.

The following equations [66, 81] describe how to find the s-curve profile's acceleration and velocity values, which are required to find the energy consumption during each move that is performed by any actuator component that follows this profile:

$$a = a_0 + j * t$$

$$v = v_0 + a_0 * t + 0.5 * j * t^2$$

$$a^2 = a_0^2 + 2 * j(v - v_0)$$

$$v = v_0 + a * t + 0.5 * j * t^2$$

$$v = v_0 + 0.5 * (a + a_0) * t$$

$$s = v_0 * t + 0.5 * a_0 * t^2 + j * t^3/6$$

where a is the final acceleration, a_0 is the initial acceleration j is the jerk (rate of change in acceleration) v is the final velocity v_0 is the initial velocity s is the distance/displacement t is the time.

3.5.1.2 Operation Modes Optimisation

Configuring actuator components with different levels of energy consumption for their different operating modes (i.e. on, idle, stand-by or off) is vital. These different modes govern the energy consumption of the components, which in turn considerably affects the manufacturing machine energy consumption. This kind of switching the actuator component into different modes of operation is necessary to operate the manufacturing machines efficiently.

However, changing the operation mode of components should be carried out carefully to prevent degrading the performance of the machine, or in some cases, it could have converse results if it happens more frequently in relatively short time. This is because that mode changing is accompanied by relatively high power peak every time the component is awakened up.

As stated earlier in Chapter 2, the amount of energy that is consumed by the *Base* components is significant and, under some circumstances, can reach 84% of the overall machine consumption. This means investing in these components can save the running costs of the manufacturing machines considerably in short time.

It is important to mention that the *Base* components should not be switched off as long as the manufacturing machine is on. They only could be set at reduced speed in case the machine is at idle state. This is because of the dangers that could happen to mechanical and electrical parts of the machine. For example, switching the ventilation fan of a control cabinet while the machine power is still on, could increase the temperature of the electronics inside the cabinet and cause malfunctions. Also, switching the lubrication pump off can lead to a high friction between the moving mechanical parts causing wears or instant damages.

For The *Ready* and the *Machining* energy consumers, normally they have stops between their tasks during one machine cycle. If this idle time is relatively long, then switching these components to the stand-by mode (where their motor drives consume less energy only to keep their electronics switched on) or complete shut off (where no energy consumed in this case as long as the component stays off) saves a lot of energy comparing to their idle modes. However, their awakening or start up times should be carefully considered to keep the system functioning as it should be [38].

The MRR (material removal rate), which reflects the cutting parameters of the *Machining* actuators, is the main independent factor of the consumed energy in the material removal processes. Therefore, optimising the cutting time will help setting them into less-energy modes and optimising the amount of energy that is consumed by these component types.

Idle losses should be minimised if mode of operation optimisation is well-implemented, because the idle time of the component is shortened and hence the associated losses.

To implement this optimisation method, software, and possibly, hardware changes to the machine are required. The software changes are often performed on the PLC program, where different actuators can be set into different operation modes according to their tasks and idle time. The possible hardware changes include:

- Replacing the aging and worn components with new efficient ones.
- Installing high efficiency components such as the IE3 lubrication pumps and high efficiency drives.
- Avoiding oversizing the components. This oversizing is the main reason that causes energy waste.
- Installing devices to help making the components more intelligent in terms of going to the sleep or standby modes whenever feasible.

3.5.2 SEQUENCE OF OPERATION OPTIMISATION (SOO)

3.5.2.1 Trajectory Optimisation

Optimising the pose of each component of a servo-actuated machine is improving the system trajectory, which in turn can improve the system energy efficiency. Alternative machine behaviours can be investigated during the design phase to determine the best optimised sequence.

For example, the standard OP1900 station that performs nut fastening on vehicle engines, has a lift actuator to lift up the engine from a pallet to a nut fastening actuator, and then it lowers it down after completing the fastening process. Another suggested trajectory that can be investigated, is to lower the fastener down to the engine that stays on the pallet, and perform its nut fastening function, then to go up to its home position. Therefore, it is worth investigating different energy consumptions by applying different machine trajectories.

The machine trajectory can be altered by changing the order of components' moves, move times, and/or move target destinations. However, any new trajectory must be take into account the safety of the machine components and human operators of semi-automatic machines. Also, the operation quality must not be degraded as a result to any proposed trajectory.

3.5.2.2 Start Time Optimisation

Another advantage of SOO is to minimise the peak energy consumption by introducing time offsets between the initiations of the component operations over the machine cycle time. Timers can be used to introduce these offsets between the components that start operating at the same time.

The proposed time offset could affect the cycle time of the machine. Therefore, it is important to validate the new design virtually before implementing it on the physical machines. Also, machine trajectory could be affected. For example, in an XY gantry assembly machine, delaying one axis will result different trajectory comparing to the original one. However, in case of two axes move a long X or Y together, then introducing time offset only to one of them could lead to skew in the mechanical linkage between them. In this case, mechanical damages occur. Therefore, virtual validation is highly important before implementing this method of optimisation.

3.6 THE EXISTING vueOne VIRTUAL ENGINEERING TOOL [59]

In this section, a brief description of the existing vueOne tool features and functions is presented, in order to give a foundation for the proposed enhancements to the vueOne from the energy prediction and optimisation perspective, as a main contribution of this research, in the following section 3.7.

For the purpose of this research, the vueOne virtual engineering environment has been used to implement manufacturing process simulation models, from which the basic information required to parameterise the energy practice efficiently is derived.

The vueOne tool is being developed by the Automation Systems Group (ASG) at the University of Warwick, and driven by the concept of a component-based system architecture [55, 56] to achieve system reusability and reconfigurability. A component is defined as a reusable, reconfigurable unit providing the data integration mechanisms for control, 3D modelling, kinematics and other data types describing a particular resource (e.g. component faults), and is central to the vueOne tool development [85]. Currently, the vueOne does 3D modelling and simulation, virtual commissioning, process planning and automatic generation of PLC codes functions but not energy consumption prediction and optimisation.

The vueOne tool is a lightweight modelling and simulation software that uses the standard Virtual Reality Modelling Language (VRML) format for three-dimensional (3D) modelling and generic Sate-Transition diagrams for control logic editing and visualisation. The vueOne tool supports modelling of several types of components such as sensors, actuators, timers, work-piece routing, human mannequin, robots and fixtures. In the vueOne tool, component geometry, kinematic behaviour and control behaviour are integrated around a common model architecture. Using the vueOne tool, modelling and simulation tasks are performed in two phases; 1) Component Modelling is a perquisite to the next phase, 2) System Modelling.

3.6.1 COMPONENT MODELLING

Components are built using the Component Builder module and then saved in the Component Library. Component Builder Module performs the following functions: 1) 3D geometry modelling, 2) kinematics modelling, and 3) control behaviour modelling. The modelled component could have any combination of these three functions (such as the sensor component that does not have geometry), the three functions (such as the actuator component), or at least one function (such as the non-control component that has geometry only).

The component modelling overview is shown in figure 3.9. Each component can be consisted of one or more construct, different constructs within each component represent the moving and stationery parts.

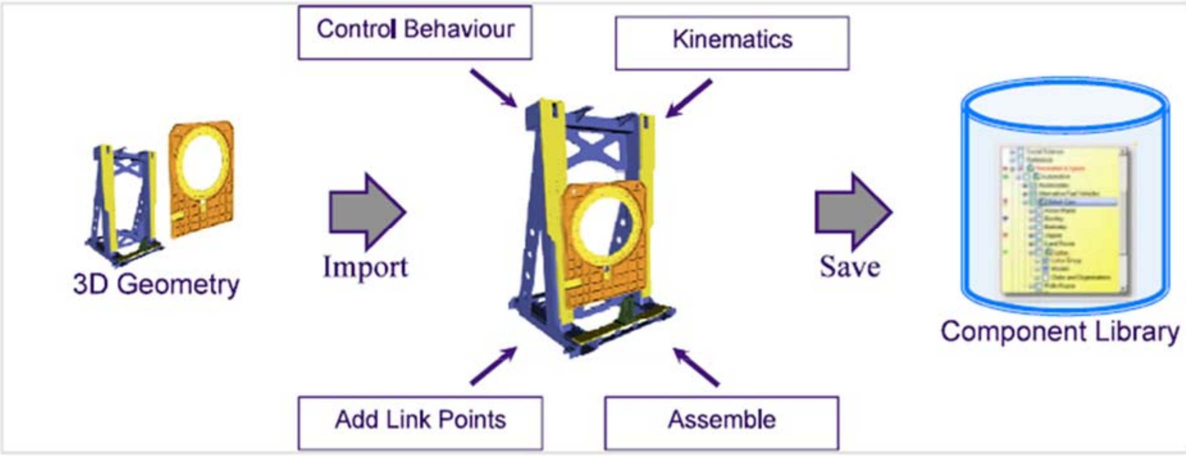


Figure 3.9: The component modelling process in the vueOne editor.

3.6.1.1 Geometry Modelling

The 3D visualisation of a component's physical attributes such as dimensions and shape are described here. The vueOne does not provide conventional CAD modelling but allows the import of 3D, surface only, VRML standard CAD geometry into the Graphic Library to significantly reduce the memory requirements of the modelled components.

From the Graphic Library, the Component Builder Module uses the available geometries to enable Lego-like assembly of components with the help of the Link Points. The Link Points are the location points from where multiple geometries get joined together. Figure 3.10 shows the Link Points of an assembled gripper to be assembled to a moving actuator.

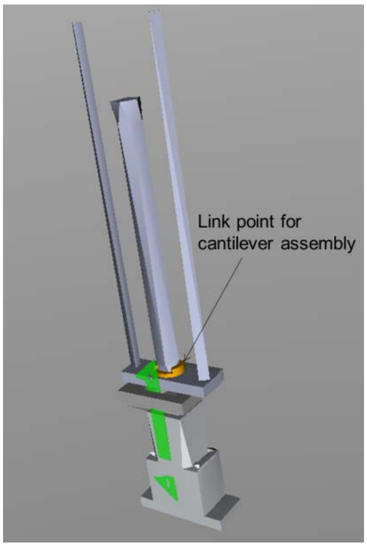


Figure 3.10: The Link Point between a gripper and a cantilever

3.6.1.2 Kinematics Behaviour Modelling

The Component Builder Module provides basic kinematics function behaviour of the modelled components; such as the type of joints (translational or rotational), duration of the move and the average velocity. It also shows the distance to be covered by the move, and the original position of the components. This description is used to enable the 3D visualisation which becomes available when geometries are correctly assembled. Figure 3.11 shows the kinematics variables.

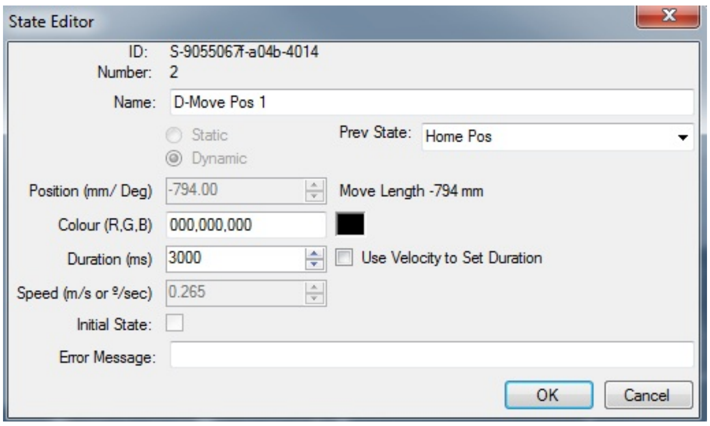


Figure 3.11: Kinematics behaviour editor in the vueOne

3.6.1.3 Control Behaviour Modelling

A generic State-Transition Diagram (STD) is used to describe the control behaviour of a component, in which component exists in a functional state and moves to the next state if the transition condition between the states is fulfilled, and hence the transition is triggered. Transitions are assigned during the System Modelling phase.

The STD within the vueOne tool has three types of states; 1) Home Initial: Must be static state that represents the component's very first state and its home position. 2) Static: It is a known component position in which the component waits till an associated transition condition is fulfilled to move to the next state. 3) Dynamic: Is a state to which a component moves between two subsequent static states; the time required to complete the move is defined and is used to calculate system cycle time. Figure 3.12 shows a simple 2-position actuator component STD and its different types of states.

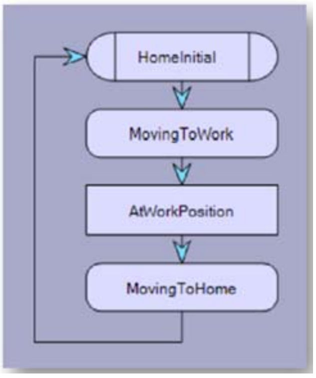


Figure 3.12: The STD and its states and transitions in the vueOne

3.6.2 SYSTEM MODELLING

At this phase, system simulation is performed to enable machine configuration, process planning, and virtual verification and validation to be achieved. A variety of system representations such as timing and state diagrams can be viewed in addition to the 3D visualisation. Once system performance has been verified, the system configuration can be exported in an XML format for further use, e.g. for automatic PLC and HMI code generation, discrete event simulation, and energy prediction and optimisation analysis.

3.6.2.1 Components Assembly

From the Component Library, components are inserted one by one and assembled via the Link Points to build the system. The operation sequence is then defined by assigning the transitions inside the components' STDs. Figure 3.13 illustrate this sub-phase.

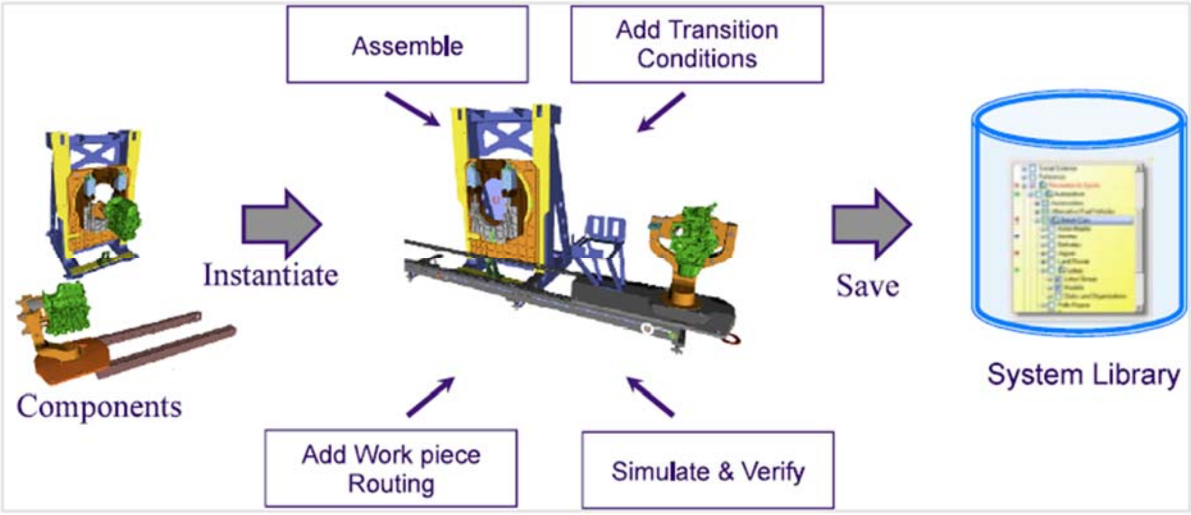


Figure 3.13: The components assembly phase

3.6.2.2 Work-piece Routing Logic

Finally, information defining how the work-piece will be routed through the system is specified step-by-step by identifying sensor, actuator and other components' status. Figure 3.14 below is an example of work-piece routing logic design.

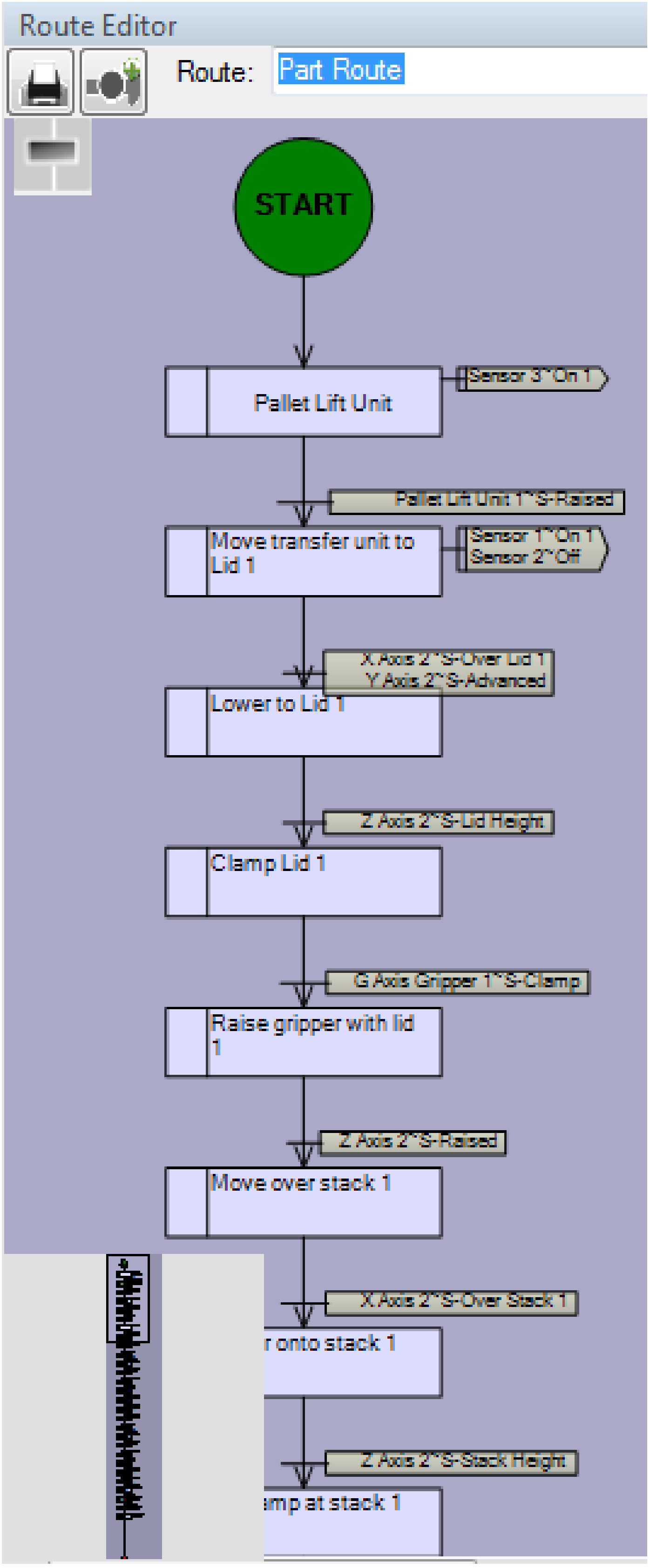


Figure 3.14: Work-piece routing logic in vueOne

3.7 THE PROPOSED ENHANCEMENTS TO THE vueOne TOOL

This section presents one main contribution of this research. To make the vueOne toolset fulfil to the aforementioned environmental requirements in terms of process energy optimisation, it should offer energy modelling and prediction of manufacturing processes during the manufacturing system lifecycle.

In order to facilitate simulation of manufacturing resources, the vueOne supports modelling of the following components: Actuator, Sensor, Virtual, SimulationOnly, NonControl, Process, Manikin, and Robot. In this research we are only interested in the Actuator components. Actuator components represent the electromechanical components that accept inputs and perform actions accordingly. This type of the vueOne components has geometry, kinematics and control behaviour.

The existing method of building components and systems in the vueOne is well suited for modelling and simulation purposes, but it has major limitations from energy modelling and optimisation perspectives. The following proposed enhancements to the Actuator component modelling are essential to estimate its energy consumption. The current modelling limitations and the proposed solutions are explained below as author's contributions:

3.7.1 LACK OF ENERGY-RELATED INFORMATION

As stated in sub-section 3.6.1.1 the geometries are built by importing surface-only VRML geometries, this gives the vueOne a big advantage as a lightweight tool over other process planning and visualisation VE tools. However, apart from shape information, other information required to predict component energy consumption, according to sub-section 3.4.1, is unavailable.

For example, to predict the energy consumption by a ball screw actuator component for one move, the vueOne must determine first the type of this energy consumer; in this case it is a *Ready* component. Then, it should know the mechanism type of this actuator, in this case it is a ball screw. Knowing this determines how to perform the inertia calculation of different parts (or constructs) of the ball screw actuator, and then the required calculation of the torque required during constant speed time. Inertia is required to find the required torque during acceleration and deceleration times of this move.

Referring to the ball screw equations mentioned earlier in sub-section 3.4.1.1, the ball screw total inertia can be found as follows:

$$Inertia_{Tot} = Inertia_{motor} + Inertia_{Trns} + \frac{Inertia_{screw} + Inertia_{load} + Inertia_{coupling} + Inertia_{Table}}{Ratio_{Trns}^2}$$

Where:

$Inertia_{motor}$: is a constant figure given in the motor datasheet, but it is not defined in the actuator component data structure of the vueOne tool.

$Inertia_{Trns}$: is the inertia of transmission mechanism (gears or gear box, or belt and pulleys). This value could be zero if the motor is directly attached to the ball screw. Also, it could be constant figure given by the manufacturer in the data sheet, but the vueOne data structure does not have an assigned place to accommodate this value.

$Inertia_{screw}$: is the inertia of the screw part. It can be calculated as follows:

$$Inertia_{screw} = 0.5 * \pi * L_s * \delta_s * r_s^2 = 0.5 * m_s * r_s^2$$

Neither the screw mass m_s nor the screw material density δ_s of them is considered currently in the vueOne data structure. Same data (in different equation) are required to calculate the coupling inertia, $Inertia_{coupling}$.

$$Inertia_{load} = m_l * l_s/(4 * \pi^2 * Eff_s)$$

Again none of the screw lead l_s or its efficiency Eff_s is defined in the current vueOne data structure. Also, the required reducing ratio achieved by the transmission mechanism $Ratio_{Trns}^2$ is not defined.

The proposed solution is to extend the existing actuator component data structure to include the aforementioned energy-related data, and enable the end user to assign these required values based on the actuator physical specifications. This should happen during the component modelling phase, using a newly provided window as part of the vueOne editor user interface.

Figure 3.15 shows part of the current data structure of the vueOne component in XML format. The proposed extension to data structure with proposed *EnergyData* child to actuator component nodes is shown in the right side. Detailed contents of *MotorAndDrive*, *PowerTransmission*, *Specifications* and *Extras* can be viewed in section 4.4. Figure 3.16 shows part of the developed Matlab code to predict the required torque for the first two moves by the X axis actuator component. The required energy related data are currently available in the Energy Optimiser tool through its user interface as explained in section 4.4.

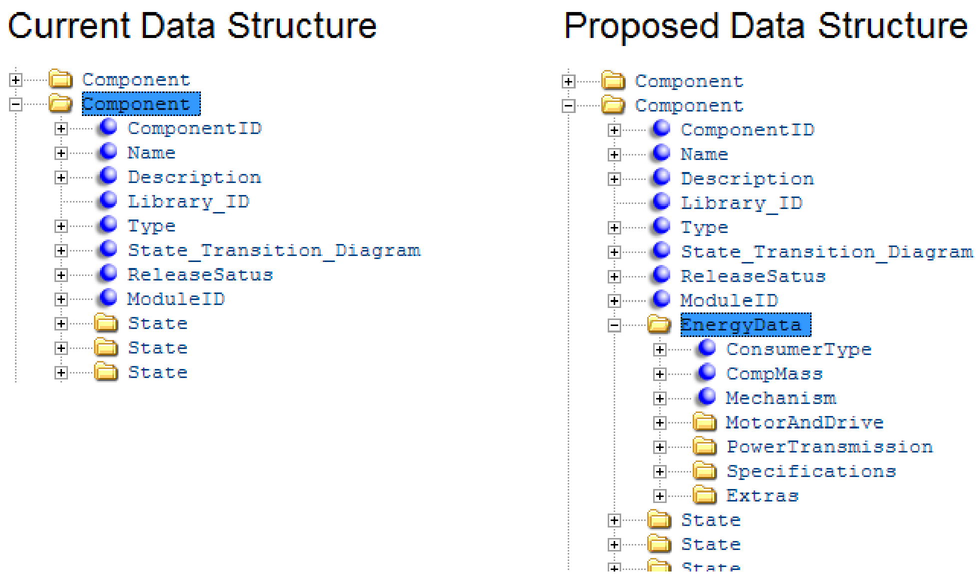


Figure 3.15: The proposed *EnergyData* to be added to the vueOne data structure

```
%%% Developed torque by X-axis motor
% 1st move: left from start pos. to pick1 pos.
XF_fr1 = XFrc_coeff * XLoad_mass * g; XF_grv1 = XLoad_mass * g; XF_tot1 = XF_fr1 + XF_grv1;
XTq1_run = XF_tot1 * screw_lead/(screw_eff*2*pi);
J_load1 = XLoad_mass*screw_lead^2/(4*pi^4*screw_eff); XJ_tot1 = J_XMotor + J_coupling + J_screw + J_load1;
XTq1_acc = XJ_tot1 * Alpha1XM; XTq1_dec = -XTq1_acc;

% 2nd move: right from pick1 pos. to place1 pos.
XF_fr2 = XFrc_coeff * XLoad_mass * g; XF_grv2 = XLoad_mass * g; XF_tot2 = XF_fr2 + XF_grv2;
XTq2_run = XF_tot2 * screw_lead/(screw_eff*2*pi);
J_load2 = XLoad_mass*screw_lead^2/(4*pi^4*screw_eff); XJ_tot2 = J_XMotor + J_coupling + J_screw + J_load2;
XTq2_acc = XJ_tot2 * Alpha2XM; XTq2_dec = -XTq2_acc;

% 3rd move: left from place1 pos. to pick2 pos.
```

Figure 3.16: The Matlab code to predict the developed torque by the X actuator component

3.7.2 INAPPROPRIATE DEFINITION OF MOTION

Currently, the kinematic behaviour modelling that is mentioned in sub-section 3.6.1.2 deals with move velocity as a constant velocity, without considering the acceleration / deceleration values and times. Thus, the definition of the moves in the dynamic states of the Component Builder is unrealistic and only intends to fulfil the simulation purposes.

Figure 3.17 shows the difference between the current vueOne velocity profiles and the realistic proposed profiles. The acceleration / deceleration time and distance in the proposed velocity profiles can vary to cover a wide range of motion profiles. These profiles can be triangular profiles where the acceleration time is the same as the deceleration time and the sum of them equals the total move time. Another profile can have very short times at both ends resulting the trapezoidal profile with relatively very long time for constant speed. Also, it is not necessary to have symmetric shape of velocity profiles; acceleration and deceleration times can be different. Furthermore, the acceleration and deceleration are not necessary to be constant values; they can be functions forming the s-curve velocity profiles as explained in sub-section 3.5.1.1.

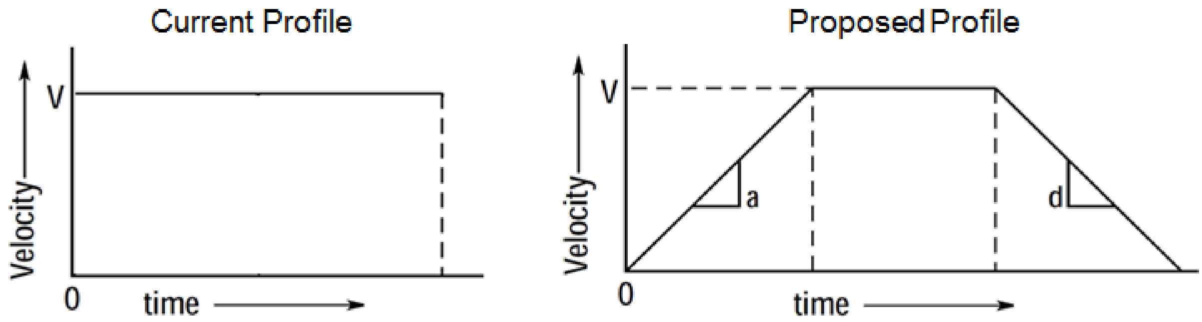


Figure 3.17: The current and the proposed motion definition to the vueOne

The proposed solution to this limitation is to extend the dynamic states data structure to include the acceleration / deceleration times as children to the *Duration* (its new proposed name instead of the old one, *Time*) node. Also, to add the acceleration / deceleration values to define completely the velocity profile of the dynamic state move. Finally, the end user should be enabled to define these necessary values on the user interface window of state editor that is shown in figure 3.11. Figure 3.18 shows the proposed versus the current data that are required to define the motion profile of the actuator component moves.

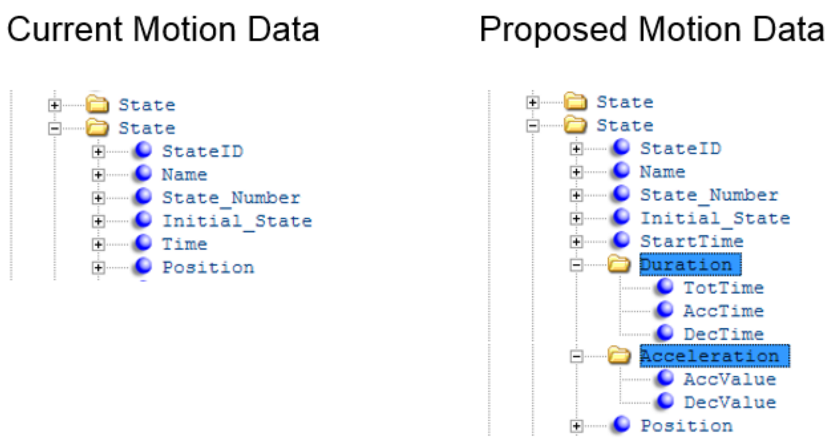


Figure 3.18: The proposed motion data to be added to the vueOne data structure

3.7.3 UNAVAILABILITY OF INTERLOCK TO AVOID SIMULTANEOUS MOVES BY ACTUATOR COMPONENTS

The dynamic states in the vueOne can be event-driven or time-driven states. When a transition condition between two subsequent static states is satisfied, the respective dynamic state between them is initiated. The transition conditions can be satisfied by a timer output, status of other components, or a sensor signal.

Currently, there are two types of interlocks in the vueOne; internal and sequence interlocks. These interlocks are defined as transitional conditions. The purpose of adding these interlocks to components' states is to define how to interoperate considering the behaviour of other components in the system.

The sequence interlocks define the conditions within the component STD, which prevent the component from moving from one static state to the next static state. Given that the interlock is a transitional condition, then proposing a special type of sequence interlock that delays different actuator components by an adjustable amount of time from moving at the same time if their dynamic states are initiated by the same transitional condition. Figure 3.19 below shows the proposed changes on the sequence interlocks on the components states. To allow this change, figure 3.20 shows the proposed dynamic state within the STD.

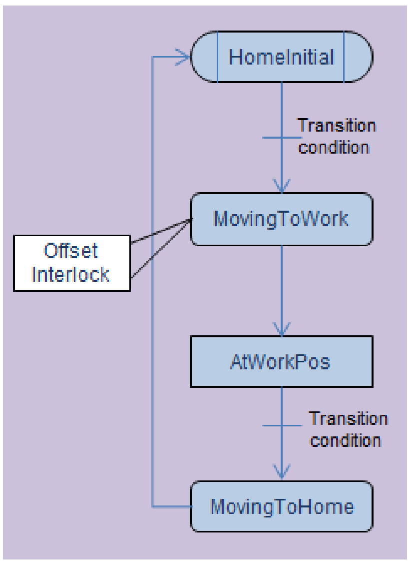


Figure 3.19: The proposed offset interlock in the STD of actuator components

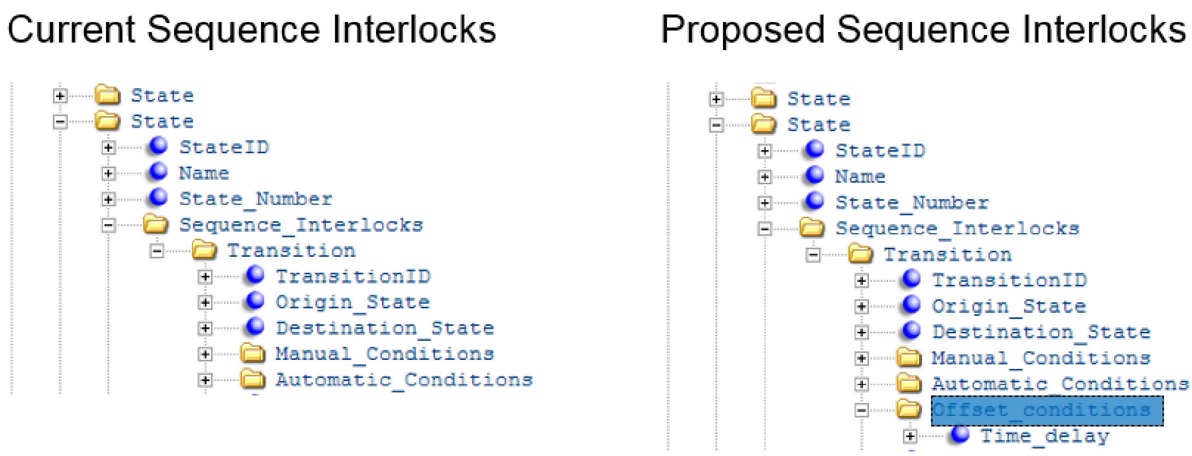


Figure 3.20: The proposed change to the Sequence Interlock data structure

The proposed modification to the Sequence Interlocks in the dynamic states of the actuator component requires a constant monitoring of the offset interlock condition. The corresponding dynamic states go into halt state if the interlock condition is fulfilled, and then a warning message appears asking the end user to modify the transitional condition or to proceed.

3.7.4 MODES OF OPERATION DURING IDLE STATE ARE NOT AVAILABLE

The actuator component performs its actions as defined in its STD and kinematic editor, where its energy consumption during each dynamic state can be predicted. However, when the actuator reaches its target destination and stops there for a while waiting to perform its next move, it also consumes energy although it is not moving. The amount of this energy consumption depends on the actuator mode of operation while it is on its static states.

Therefore, each static state of actuator’s STD should specify the mode of the actuator, weather it is idle, stand-by or off. This can be achieved during defining the actuator’s control behaviour in the state editor as shown in figure 3.21.

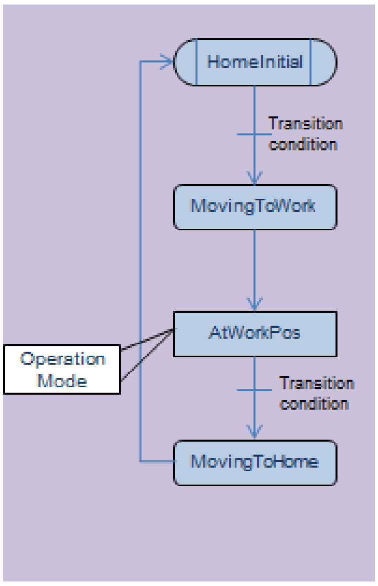


Fig. 3.21: The proposed mode of operation tag in the static states of the actuator STD

Figure 3.22 shows the proposed mode of operation data to be added to the static state data structure.

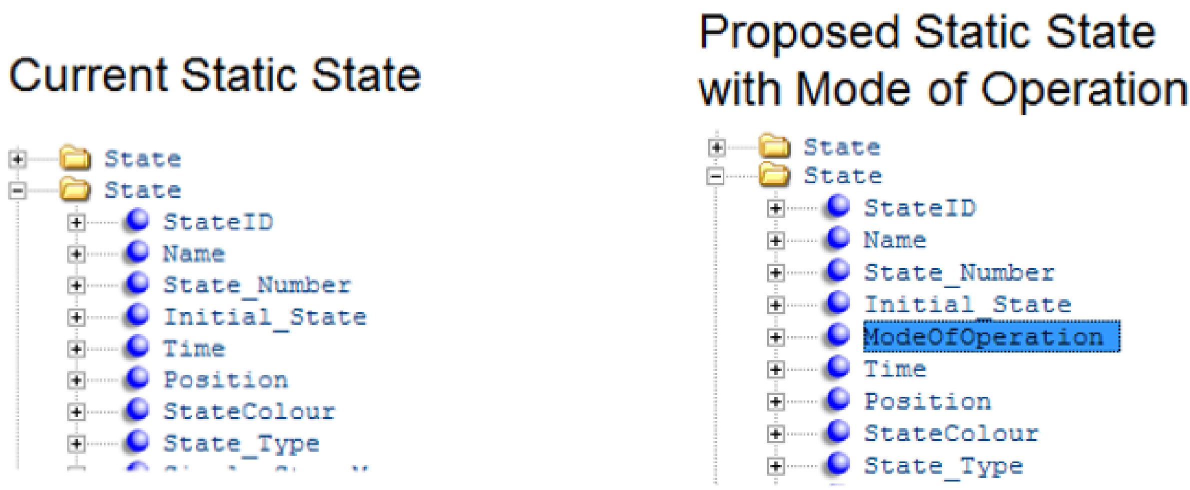


Fig 3.22: The proposed change to the static state data structure

3.7.5 WORK-PIECE MASS IS NOT DEFINED

The energy consumption of any actuator component varies depending on weather it is carrying the work-piece or not. Thus, when the actuator component moves carrying the work-piece, the mass of the later must be known in order to predict the energy consumed by this actuator during this particular move as shown in the equations of sub-section 3.4.1.1.

However, the work-piece mass in the vueOne tool is not defined. Therefore, it is proposed to include the work-piece mass in the part routing data structure, and in the actuator component dynamic states. This is required to enable the end user to state if the work-piece is to be carried or not. Figure 3.23 shows the proposed addition of the work-piece mass to the part routing and the actuator states.

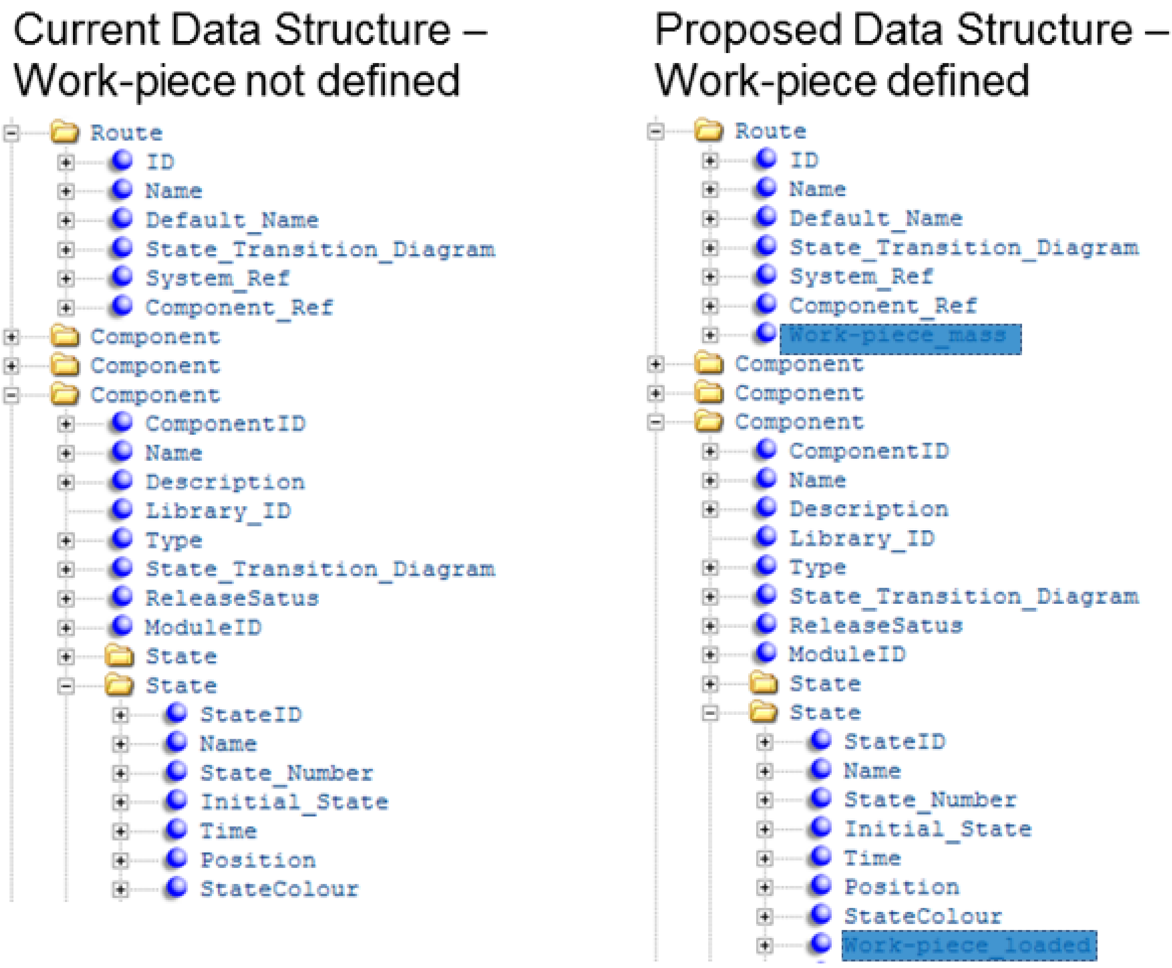


Fig 3.23: The proposed change to the work-piece routing data structure

3.8 THE DEVELOPED ENERGY OPTIMISER TOOL

To facilitate implementing the CBEO framework, the Energy Optimiser tool has been developed by the author in MATLAB programming Language. The interaction between the Energy Optimiser and the existing vueOne tool is shown in figure 3.24. The Energy Optimiser tool is a prototype to prove the optimisation opportunities that can be achieved by fully integrating the proposed CBEO framework with the existing vueOne toolset, which is presented in section 3.6. Currently, the Energy Optimiser tool has been developed as a stand-alone tool that requires its inputs from: 1) the vueOne toolset, 2) end user inputs for the required energy-related data that is not available from the vueOne tool, and 3) actual energy consumption data that is taken at the operation machine phase.

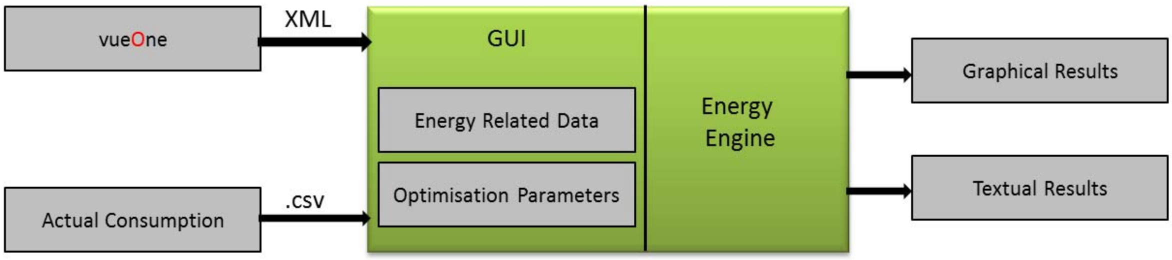


Figure 3.24: The interaction between the Energy Optimiser and the vueOne toolset

The information of an assembly machine, which has been modelled in the vueOne, can be stored in the eXtensible Mark-up Language (XML) format, and then the XML file is generated by the vueOne. This XML file can be imported into the Energy Optimiser tool, where some of the required information for energy prediction, that is currently available by the vueOne such as total move times and positions, is extracted.

The rest of the required energy-related information that is not currently available by the vueOne tool such as; the operating conditions, the mechanism specifications, the power transmission specifications, etc., can be specified for each actuator through the Graphical User Interface (GUI), which has been developed for this research and explained in Chapter 4. Also, the desired optimisation methods such as; modes of operation, motion profiles and system trajectory can be selected. Furthermore, the actual energy consumption information in the Comma-Separated Values (CSV) format can be imported to the Energy Optimiser tool for comparison and tuning purposes.

When all the required information for energy prediction is imported and defined, and the desired optimisation methods are selected, the Energy Engine predicts the optimised energy consumption of the machine. The Engine also generates the energy results in graphical and textual formats.

Figure 3.25 explains how the Energy Engine works conceptually. The components are classified in the Energy Engine based on their type from energy perspectives. For a *Ready* component, the available energy related data that provides details about component physical attributes is used to: 1) calculate constructs inertia, 2) the acting forces, and 3) the required torque to overcome these forces during constant speed phase. The data that comes from the STD, which describes the dynamic and the static behaviours of the component, accompanied by the selected optimisation parameters, are then used to find the acceleration /deceleration torque, as well as the normal running torque. Thus, predicting the energy consumption per *Ready* actuator per move is achieved, including the *Idle* losses. Same calculations are performed for all moves achieved by the component. The same calculations apply for all other *Ready* components.

The user interface enables the end user to enter the rated power of the *Base* components, given the system cycle time, the energy consumption by these components is also predicted. Therefore, for assembly machine, the aggregate value of the *Ready*, *Base* and *Idle* components' energy consumptions with respect to the machine cycle time, represents machine whole energy consumption.

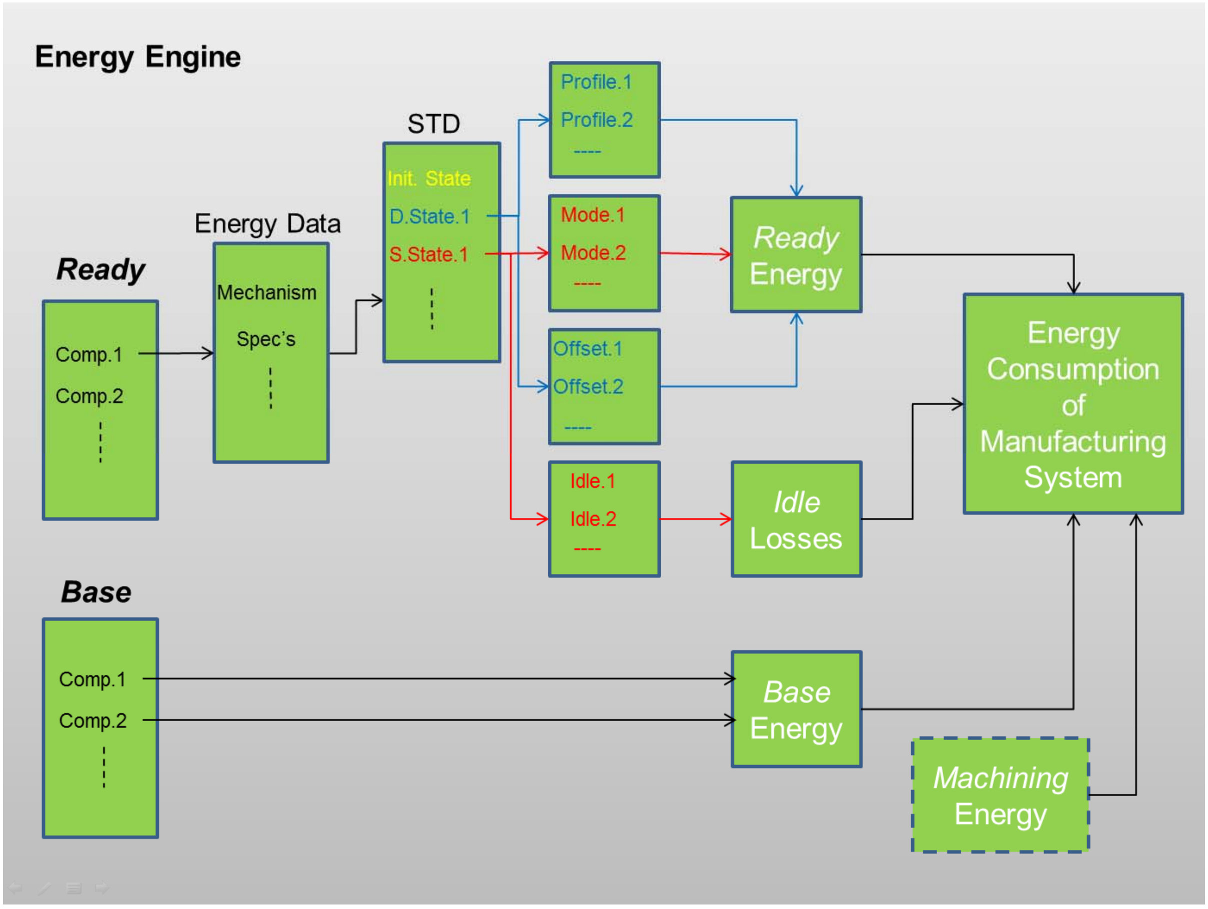


Figure 3.25: The conceptual design of the Energy Optimiser software architecture

The flow diagram of the developed software is shown in figure 3.26. The following detailed procedure illustrates the process of predicting and optimising the energy consumption by assembly machines:

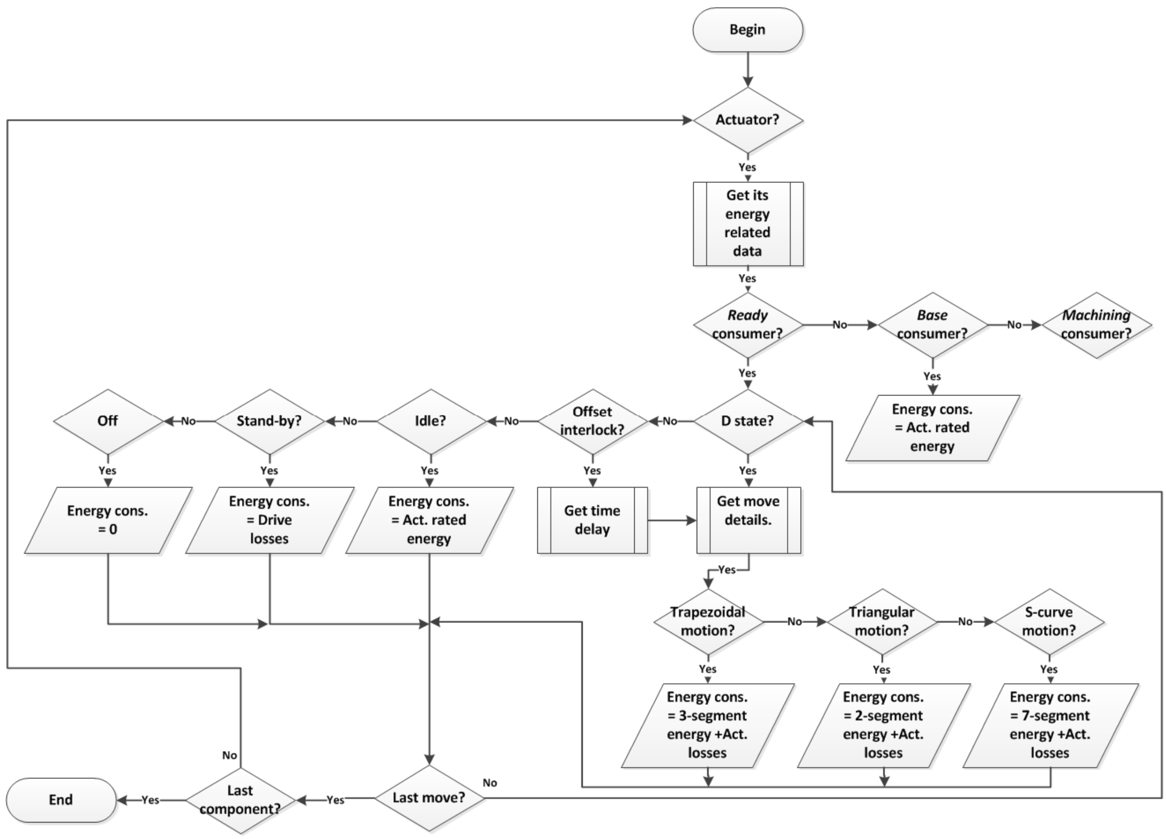


Figure 3.26: The flow diagram of the Energy Engine.

1. The developed Energy Engine loops through all machine components. When an actuator component is found, the tool collects its energy-related data by extracting the available data from the imported XML file, and the rest of data which is specified in the GUI.
2. The engine decides to which energy consumption category (*Ready*, *Base* or *Machining*) the component actuator belongs. In the case of *Base* actuator, the energy consumption is the rated consumption.
3. If the actuator is a *Ready* type component, then the software gets its STD information. In the case of not moving actuator, the engine determines the cause of this status by testing if there is any offset interlock is active on its dynamic state.
4. In case of the presence of an offset interlock, which prevents the component from moving, then the engine gets the time delay specified to this interlock. This is important

in order to allocate the energy consumption of this move by this actuator properly with respect to machine cycle time.

5. If the *Ready* component is on one of its static states, then the engine predicts its energy consumption by identifying its mode (idle, stand-by or off). Accordingly, the energy consumption can be determined based on the energy value that is associated with each mode. This energy value of each operation mode is defined according to some rules as mentioned in sub-section 4.5.3.2.
6. When the *Ready* actuator dynamic state is examined, the selected velocity profile, the move time, and the distance covered by this move determine the energy consumption during every time segment of the move. In the case of the trapezoidal motion profile, the energy consumption will be calculated over three time segment: 1) acceleration, 2) constant velocity, and 3) deceleration segments. For the triangular motion, there are only two segments: 1) acceleration and 2) deceleration. However, the s-curve motion is formed from seven segments: 1) acceleration ramp up, 2) constant acceleration, 3) acceleration ramp down, 4) constant velocity, 5) deceleration ramp up, 6) constant deceleration, and 7) deceleration ramp down segments. The energy losses by the actuator drive and its motor are implicitly modelled into the energy consumption that is resulted from each motion segment.
7. Once completing the energy consumption calculation for this move, the engine tests the STD information if there are more move(s). If yes, the aforementioned procedure is initiated again.
8. If the STD has no more dynamic states, then the engine gets out of this actuator's STD, and examine if there are other actuator components in the machine to predict their energy consumption, otherwise it stops.
9. Finally, the process of energy consumption prediction and optimisation is completed, and the results of each actuator and the whole machine are generated and visualised to the Energy Optimiser GUI.

Figure 3.28 shows the proposed result representation feature to be added to the vueOne toolset in case of the CBEO framework is integrated to it, while figure 3.27 shows the existing cycle timing diagram that is currently generated by the vueOne tool. The energy consumption by each component versus its corresponding operation time needs to be represented in the system representations. Thus, the whole system estimated energy consumption can be assessed and optimised. The modelled system energy consumption is the sum of the contributing components' consumptions as shown in the bottom of figure 3.28.

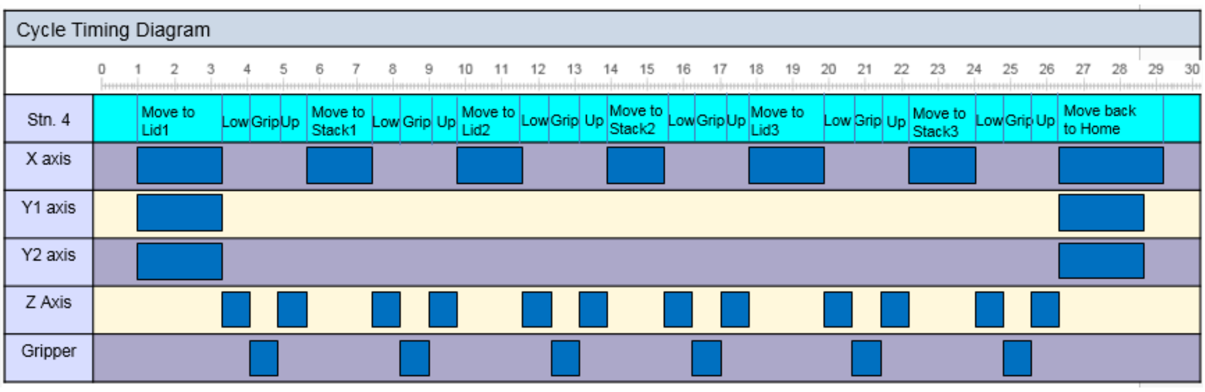
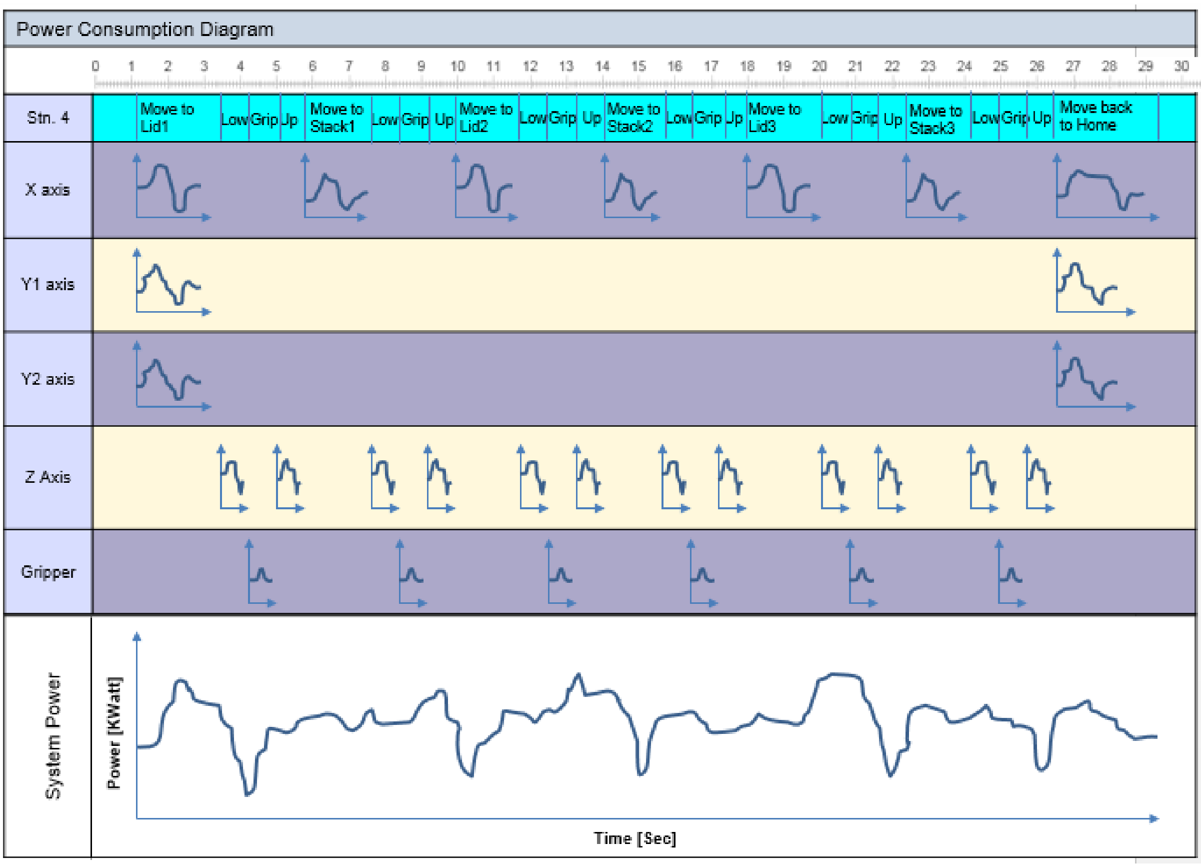


Figure 3.27: The existing cycle timing diagram of the vueOne tool



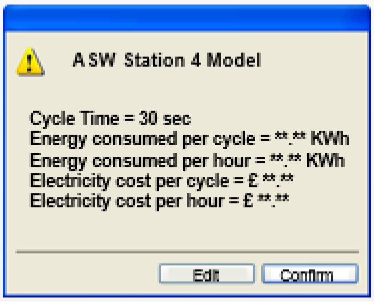


Figure 3.28: The proposed Power Consumption Diagram to the vueOne tool

3.9 SUMMARY

This chapter has presented a framework and its software that enables the energy prediction and optimisation of manufacturing machines by benefiting from their virtual model, which have been created already in the vueOne VE tool. The functional requirements of the energy optimisation software have been identified in order to propose an applicable and realistic solution.

The novel CBEO framework has been designed on the basis of the solid and established IMC theory, which enables the energy prediction and optimisation throughout the entire lifecycle of assembly systems. The proposed CBEO framework exploits the state-transition energy modelling method, and integrates the different energy optimisation methods, using the component-based approach in a virtual engineering environment, and benefits from the existing energy monitoring techniques in order to achieve accurate and robust control of the energy to be consumed by assembly machine throughout its lifecycle.

In addition to the perfect energy threshold targeting feature, this proposed closed-loop model-based feedback CBEO framework compares the actual energy consumption with the desired consumption that is set at the design phase. Also, the CBEO can inherently compensate for the unplanned disturbances that could occur at the machine operation phase; such as changes in loads and components aging and wear. This requires continuous update for the component library.

A detailed procedure for components energy prediction and modelling verification have been explained for five different mechanisms that are commonly used in assembly machines. Also, four methods of energy optimisation at the component and machine levels have been introduced. Component Optimisation (CO) and Sequence of Operation Optimisation (SOO) methods can be implemented by software and/or hardware (re)design and/or (re)configuration of assembly systems.

The way of modelling components and machines in the vueOne VE toolset has been critically reviewed, and number of limitations that prevents the CBEO framework to be integrated to the vueOne tool have been identified. To address these limitations, solutions have been proposed, table 3.1 below summarises the vueOne limitations and the proposed solutions.

Table 3.1: The vueOne toolset limitations and the proposed solutions

No.	The vueOne Limitation	The Proposed Solution
1.	Lack of energy-related information.	Provision for expanding the component data structure to accommodate energy-related information during the component geometry modelling.
2.	Inappropriate definition of motion.	Provision for adding acceleration/ deceleration times and values to the kinematic behaviour modelling.
3.	Unavailability of interlock to avoid simultaneous moves by actuator components.	Provision for special type of Sequence Interlock in components' dynamic states.
4.	Modes of operation during idle state are not available.	Provision for components' static states to accommodate modes of operation data
5.	Work-piece mass is not defined	Provision for defining work-piece mass as part of Routing.

Finally, the implementation of the CBEO framework has been achieved by developing the Energy Optimiser software in MATLAB programming language. The software extracts the currently available data of machine components from vueOne XML file, and the rest of the required information is entered by the end user in a GUI. The principle and data flow of the Energy Engine that does the energy consumption prediction and optimisation has been presented. More details about the developed Energy Optimiser tool are available in the next Chapter 4.

CHAPTER 4

CASE STUDY AND EVALUATION

4.1 INTRODUCTION

In this chapter the proposed CBEO framework and its Energy Optimiser too are to be validated against an industrial case study, which is already established. This established industrial station is virtually modelled and visualised using the vueOne tool set.

The assembly station is described in terms of its components, and its sequence of operation to perform its functions. The challenges and restrictions which have been emerged during the experiments because of the nature of the station and the measuring apparatus are also highlighted. Clear and detailed operational steps during set-up and performing the experimentation has been listed in order to improve the clarity of the results.

Different experiments at both component and station level have been carefully designed and carried out. The purpose of these experiments is to capture the required key enablers that influence the level of energy consumption by the assembly station, and to validate the proposed Component Optimisation (CO) and Sequence of Operation (SOO) methods. The limitations of these experiments have been highlighted and their impacts on results' accuracy have been discussed and evaluated.

4.2 CASE STUDY

4.2.1 AUTOMATION SYSTEMS WORKBENCH

A full-scale Automation System Workbench (ASW) is installed at Warwick Manufacturing Group (WMG) to support the research and development activities of Automation Systems Group (ASG). It is a modular and reconfigurable system and hence the application can be progressively changed as new requirements emerge. Machine stations can be exchanged physically and also virtually, i.e., new virtual stations model can be swapped in (and out) in place of physical stations.

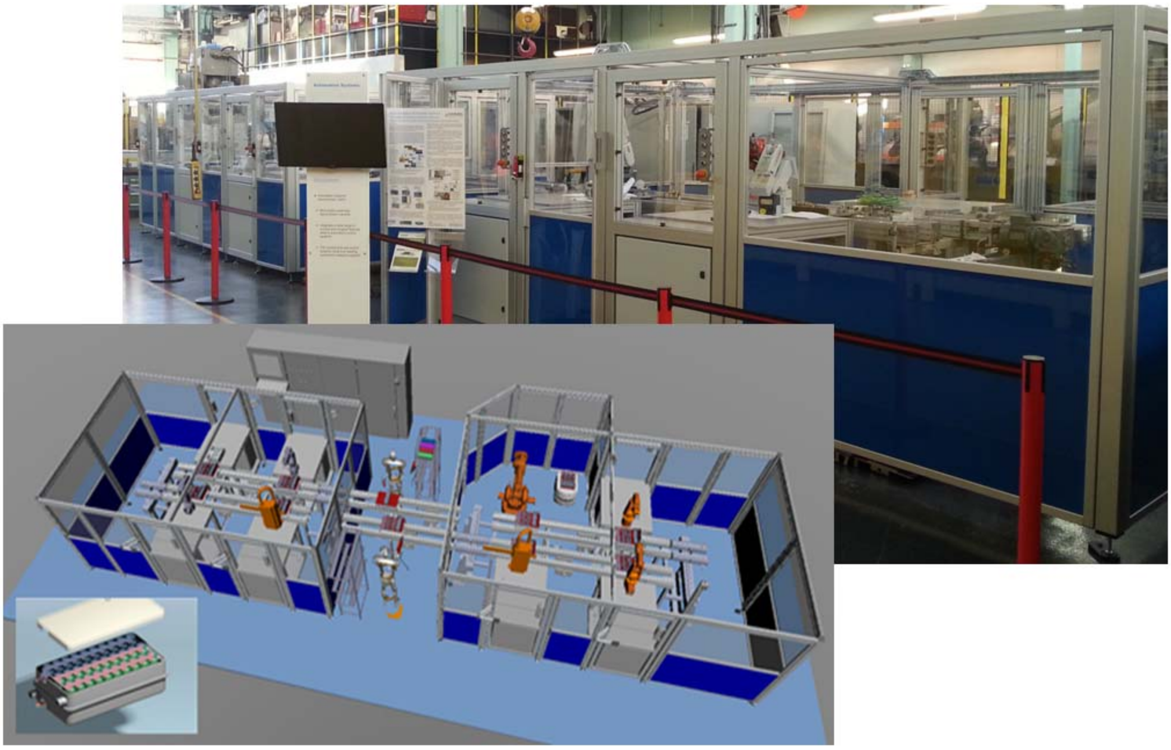


Figure 4.1: Automation System Workbench (ASW)

The ASW features state-of-the-art control system and automation equipment is from leading vendors, e.g., Siemens, Bosch-Rexroth, Rockwell Automation, ABB, Schneider Electric, Mitsubishi, Festo and SMC. The system has been implemented to support the latest control system design and programming standards. The ASW aims to provide a full-scale demonstrator for new manufacturing automation methods, tools and technologies with the objective of supporting the entire lifecycle, e.g., enabling the digital validation, verification and visualisation, control code generation, energy optimisation and cloud-based engineering services. The ASW is also used with industrial collaborators (e.g., Jaguar Land Rover, Ford Motors and their supply chains) for demonstration of product assembly. The ASW is currently configured to carry out a battery sub-module assembly demonstration as a part of an Innovate UK project. The product assembly consists of 18650 form-factor cylindrical cells to be assembled into a sub-module incorporating bus-bars and an integrated cooling system.

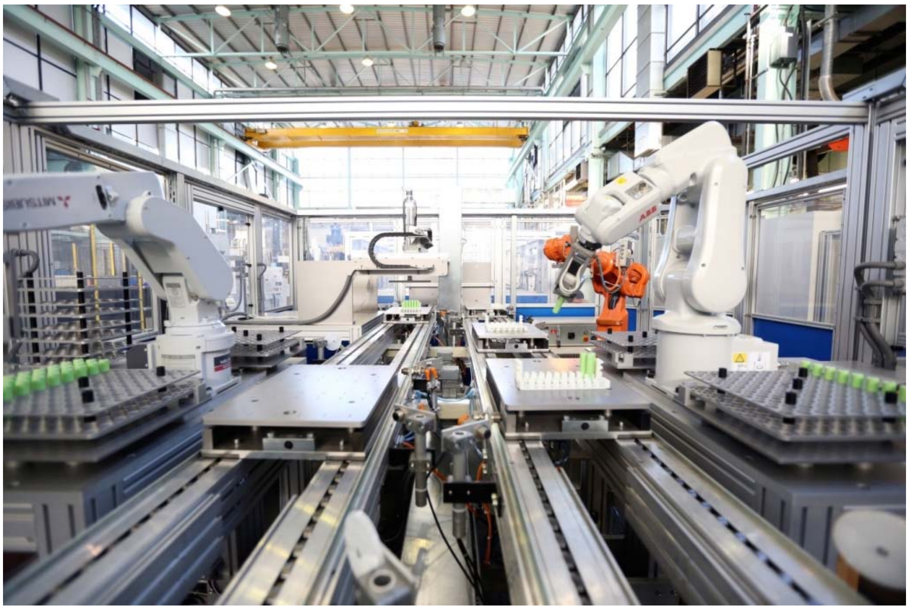


Figure 4.2: 18650 form-factor cylindrical cells being assembled

The ASW features both legacy systems, and the current state-of-the-art installed factory automation. It includes an Industrial Internet of Things (IIoT) demonstration and cyber-physical systems functionality including augmented reality systems.

- The ASW is a test bed to enable both research and development into new advanced automation systems and related lifecycle engineering tools, and also a full-scale educational system. The system enables users to be exposed to state-of-the-art current and envisaged future automation systems engineering methods.
- The aim of the ASW-based research is to show how, on an industrially representative platform, future automation systems can be evolved, implemented, and evaluated in an industrially representative manner.

4.2.2 PICK-AND-PLACE STATION

For proof of concept demonstration, a case study of a pick-and-place automatic workstation is presented. This station, station 4, is shown in figure 4.3. After the arrival of the pallet, the electric gripper picks three lids, one at a time, which sit on the pallet that moves on a conveyor. The same pallet also carries three populated battery stacks as shown in the figure 4.3. The gripper places one lid on the top of each battery stack. Finally the pallet, with the assembled battery sub-modules, moves on to the next station in the ASW.

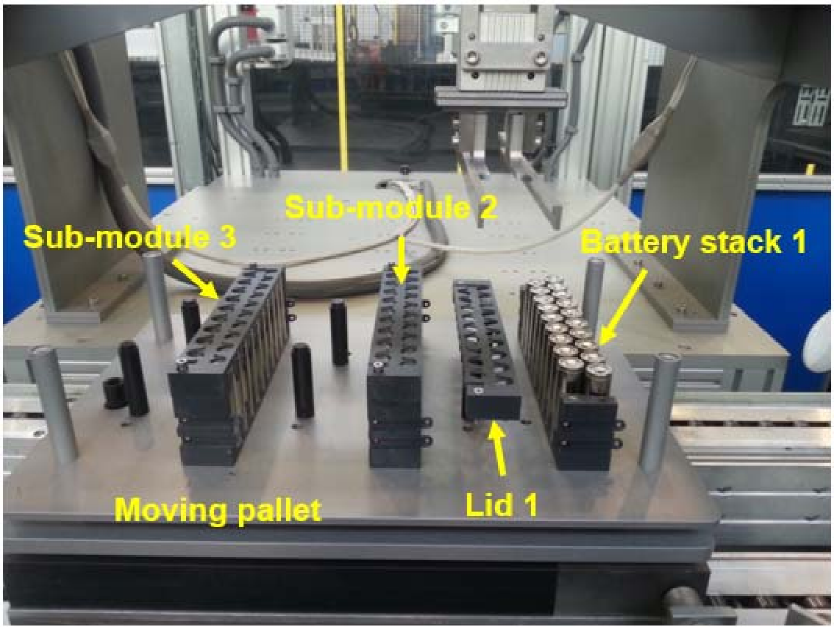


Figure 4.3: Lid 1 to be picked up by the gripper and then placed on the top of battery stack 1

The sequence of operations and the virtual model developed in the vueOne tool are shown in figures 4.4 and 4.5.

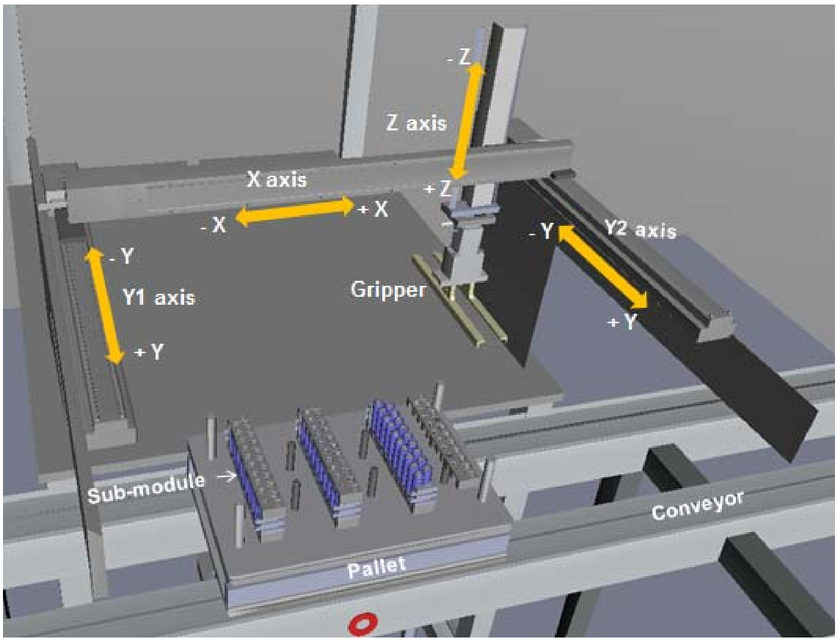


Figure 4.4: vueOne virtual model of station 4

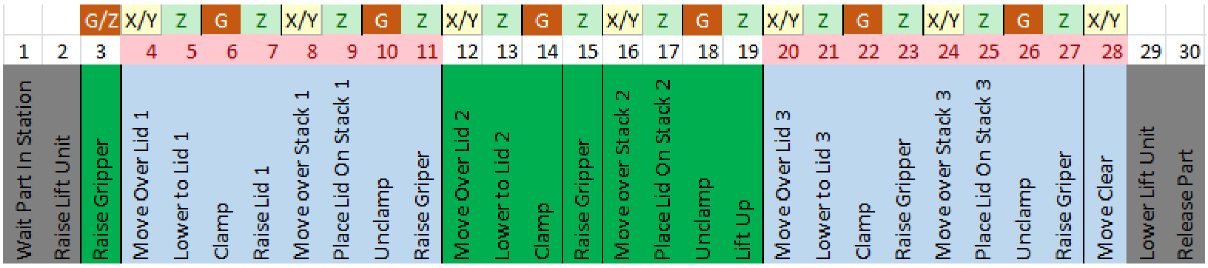


Figure 4.5: Station 4 sequence of operation

The pick-and-place station is a four-axis gantry with a fifth motor for its electric gripper as listed in table 4.1:

Table 4.1: Station 4 actuating components

Item	**Type - Description**	**Part Number**	**Task**	**Quantity**
1	Electric Gripper, Series LEH, Z Type (2 Fingers)	LEHZ32K2-22	Fitted to the Z axis of a Cartesian arrangement. Stepper motor driven (24 V_{DC}).	1
2	Electric Actuator, Series LEY, Guide Rod Type, Series LEYG	LEYG25LDB-200B	Z-axis of the Cartesian arrangement. Stepper motor driven (24 V_{DC}).	1
3	Electric Actuator, Ball Screw Drive, Series LEFS.	LEFS25B-600	X-axis of the Cartesian arrangement. Stepper motor driven (24 V_{DC}).	1
4	*Support Guide*, Ball Screw Drive, Series LEFG.	LEFG25S-600	X-axis of the Cartesian arrangement. No motor required	1
5	Electric Actuator, Ball Screw Drive, Series LEFS.	LEFS25B-400	Dual Y-axis of the Cartesian arrangement. Both are stepper motor driven (24 V_{DC}).	2

Figure 4.6 below explains the hierarchy of ASW and station 4 actuating components.

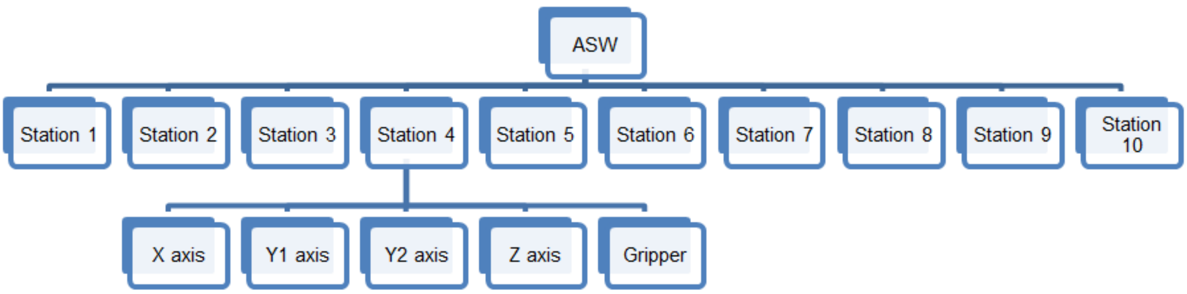


Figure 4.6: ASW hierarchy

4.3 ENERGY MEASUREMENTS

4.3.1 DESIGN OF EXPERIMENTS

The importance of undertaking these experiments is to verify the predicted energy consumption of a virtual model against the measured energy consumption of the physical station (and its components). This verification procedure is necessary in order to populate the Component Library by verified component models to be (re)used as explained in sub-section 3.4.2. The experiments have been designed to investigate the energy optimisation opportunities that were discussed in section 2.8 in terms of component acceleration and idle time, and system trajectory and sequence of operation. Therefore, the CO and SOO that were proposed in section 3.5 can be implemented, and their impacts on the whole station consumption can be quantified and analysed.

Only one component is considered by each experiment, since the interest of this research focuses on component-based domain, and how the component configuration affects its energy consumption as well as the whole machine energy consumption. Also, for each experiment, only one parameter (acceleration value, component operation mode or sequence of operation) is altered whereas other parameters stay as in their original settings and configurations.

Therefore, the experiments are categorised into two groups; one for CO experiments, and the other for SOO experiments as detailed in the following sub-sections. Since the X axis performs number of moves, and each move takes enough time to be captured by the measuring device, the X axis component is considered to be the candidate axis for experiments A1 and A2, where different motion profiles applied for axis moves. In experiment A3, since both Y Axes (Y_1 and Y_2) stay idle during station operation for a relatively long time, so they are considered to be most suitable to be switched into stand-by mode. In order to change the station trajectory, the X axis is required to alter its moves' target positions as in experiment B1. Finally, a time offset between the X axis and both Y axes starting times is introduced to avoid high spikes, this is done in experiment B2.

4.3.1.1Group A (CO)

Experiments in this group investigate the impact of the acceleration/deceleration values of the X axis moves on the whole station's energy consumption. The original moves of this axis follow trapezoidal velocity profiles with acceleration = deceleration = 2000 mm/sec^2 and constant velocity of 125 mm/sec regardless the total move time and total distance covered by each move. Consequently, each move has different trapezoidal velocity profile comparing to other moves. Therefore, new identical trapezoidal velocity profiles have been designed for each move as in the experiment A1, as well as new identical triangular velocity profiles have been designed for each move as in the experiment A2.

- **A1**, Trapezoidal velocity profile: All the moves of the X axis follow the same velocity profile where: acceleration time = deceleration time = constant velocity time = total move time / 3. Acceleration distance = deceleration distance = total move distance / 4, and constant velocity distance = total move distance / 2. Therefore, the resulted velocity profiles for all X axis moves have the same shape as shown in figure 4.7.

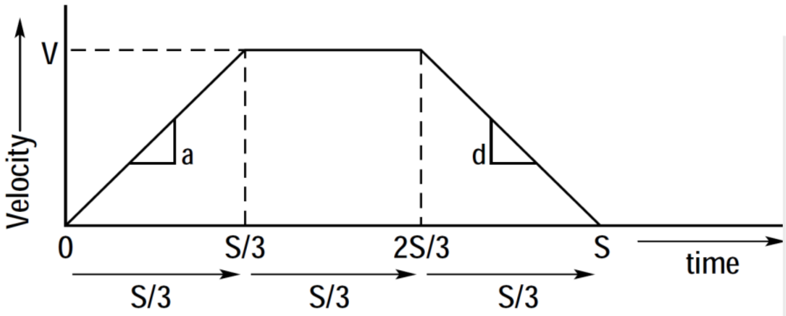


Figure 4.7: suggested trapezoidal velocity profile

- **A2**, Triangular velocity profile: All the moves of the X axis follow the same velocity profile where: acceleration time = deceleration time = total move time / 2, constant velocity time = 0. Acceleration distance = deceleration distance = total move distance / 2, and constant velocity distance = 0. This suggested profile is shown in figure 4.8 below.

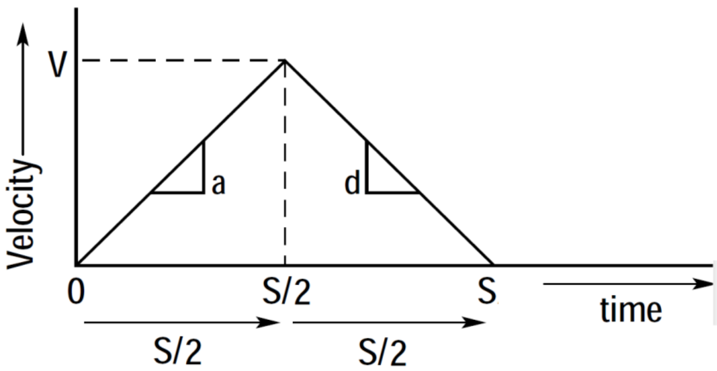


Figure 4.8: suggested triangular velocity profile

- **A3**, Y axes to stand-by mode: This experiment investigates the impact of switching both Y axes into the stand-by mode on the component and the station energy consumption. It also compares the energy consumption by these axes in their original idle state and the proposed stand-by state.

4.3.1.2Group B (SOO)

The objective of performing these experiments is to highlight the impact of different sequence of operations on the whole station energy consumption.

- **B1**, New station trajectory: Instead of following the original sequence of pick and place positions, an alternative sequence is suggested to pick and place positions. The new sequence required changes to be occurred on the X axis positions (left-and-right axis) as follows:

  Original sequence:

  PickLid1-PlaceOnModule1, PickLid2-PlaceOnModule2, PickLid3-PlaceOnModule3.

  New sequence:

  PickLid1-PlaceOnModule3, PickLid3-PlaceOnModule2, PickLid2-PlaceOnModule1.
- **B2**, Offset X and Y axes starting times: In the original configuration of station 4, X axis and both Y axes start working at the same time in their first moves to the first pick position on the pallet. Similarly, they start moving at the same time on their way back to move clear of the pallet after placing the third and last lid. The suggested time offset for this experiment introduced a slight time shift between these axes, preventing them from start moving at the same time to avoid high power spikes.

4.3.2 LIMITATIONS OF THE EXPERIMENTS

During the process of designing the aforementioned experiments, some difficulties and challenges have risen because of hardware and software limitations. These limitations have restricted the optimisation opportunities of both CO and SOO that were discussed in section 2.8 and section 3.5.

At the component level, acceleration optimisation could be investigated further if the motor drives that are attached to the station axes had the ability to support the energy-saving S-curve velocity profile. The installed LECP6 SMC drives only support trapezoidal and triangular velocity profiles. It could be very useful to design an experiment within Group A to see the impact of the X axis motor drive, with S-curve velocity profile, on the energy usage of the X axis and the whole station 4.

Also, at the component level, switching Y axes into stand-by mode are found to be more feasible as these axes stay idle for long time. However, switching the Y axes completely off is expected to save even more energy, but it requires installation of external hardware devices, which is currently not possible, since the ASW is in the commissioning phase.

At the station level, the original station trajectory is: X and both Y axes move together, at the same time, from Home position to 1st lid picking position. After performing all the pick and place operations, they move back, at the same time, to the Home position from the 3rd and last lid placing position. The station, during these first and last moves, takes diagonal path during these two moves.

Investigating the energy saving possibility by altering this original trajectory by another one is expected to change the amount of station energy consumption. The new trajectory suggests that the station moves from Home position along one axis (X or Y) only to an intermediate position, then moves along the other axis until it reaches the 1st lid picking position. Also, it takes the same (or the other available) L shape path from the 3rd lid placing position on its way back to Home position after placing the 3rd lid. However, achieving this proposed trajectory, within the same cycle time as a restriction, requires higher velocity and acceleration / deceleration values for the three axes (X, Y_1 and Y_2). Given the axes drives' maximum acceleration of 3000 mm/sec^2 and maximum velocity of 272 mm/sec, achieving this proposed trajectory is not possible, because the suggested moves require greater values than the existing hardware maximum values.

4.3.3 INSTRUMENTS OVERVIEW

As illustrated in sub-section 4.2.2, axes motor controllers are supplied by 24 V_{DC} comes from 3-phase AC to DC power converter. Therefore, the *Base* components (in this case they are HMI screen, PLC CPU, IOs and interface card) consumption equals to the difference between the overall income 3-phase power to station 4 cabinet, that is measured using the Fluke device as explained below, and the sum of the consumed DC power by 5 motor controllers (4 axes and 1 gripper), that is measured by five channels on Voltech device as explained below.

Fluke 1736 Portable Power Logger is used to measure the energy consumption by the whole station. The device comes with 4 flexible current probes for measurement of AC 3-phase current and neutral current and 4 voltage measurement leads.

Voltech PM6000 Portable Power Analyser is a 6-channel power analyser with bandwidth 0MHz – 10MHz which allows it to measure DC to AC 3-phase power. The average logging time is 0.33 seconds. 5 channels of this device are used to measure the 4 station axes and the gripper energy consumption. Figure 4.9 shows the wiring diagram of axes controllers inside the control cabinet where the device channels are connected.

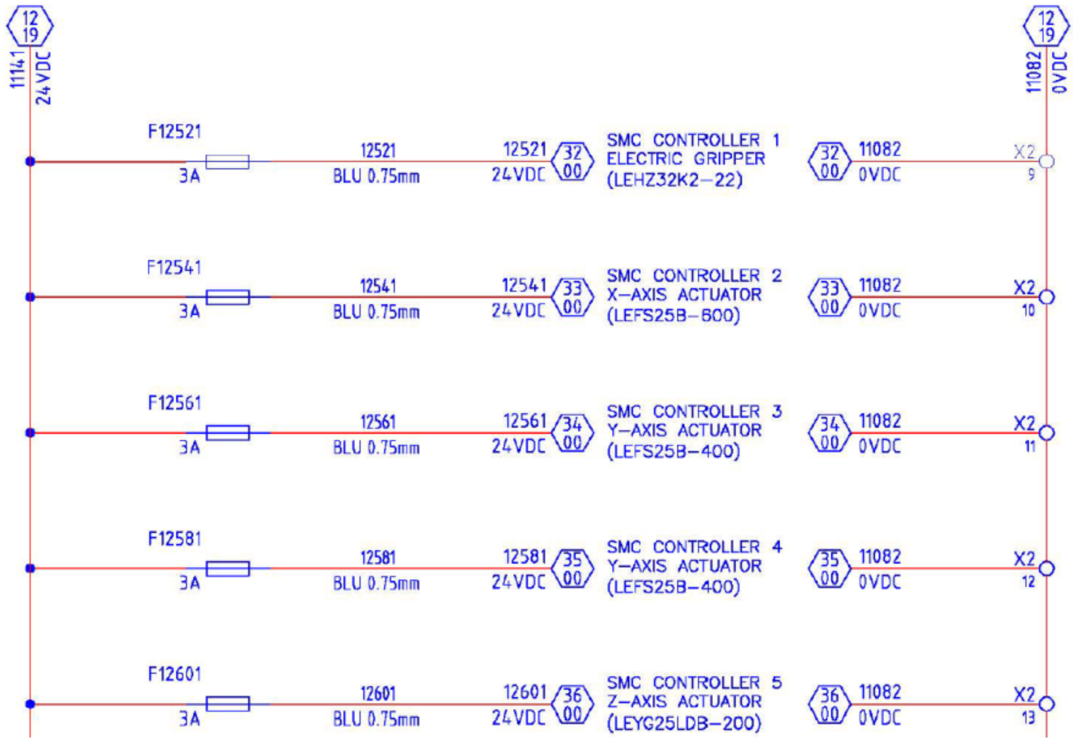


Figure 4.9: Electrical wiring of SMC motor controllers

The wiring of the Voltech PM6000 measurement channels and the motor controllers are identical and are done for each controller as shown in figure 4.10.

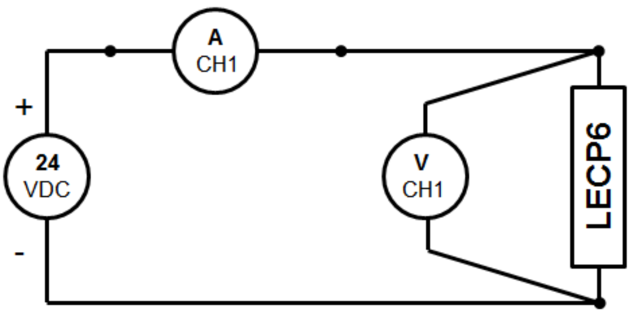


Figure 4.10: Voltage and current wiring required on Voltech PM6000 channel per motor controller

Finally, figure 4.11 shows the established wiring of both the Fluke 1736 and Voltech PM6000 devices to record energy consumption data of station 4 and its components.

Figure 4.11: The wiring of power measurement devices to station 4

More details about configuring both devices and wiring them into station 4 is available in Appendix A.

The difference between Fluke device reading and the sum of the Voltech PM6000 channels' readings is the energy consumption by *Base* components of the station 4, i.e. the HMI screen, the PLC power supply and the AC to DC power converter.

4.4 THE ENERGY OPTIMISER

Figure 4.12 shows the front panel of the Energy Optimiser tool that has been developed as a main contribution and an outcome of this research. Currently, it is an add-on prototype to the vueOne toolset in order to prove the capabilities of the proposed the CBEO framework, and in future can be fully integrated to vueOne toolset.

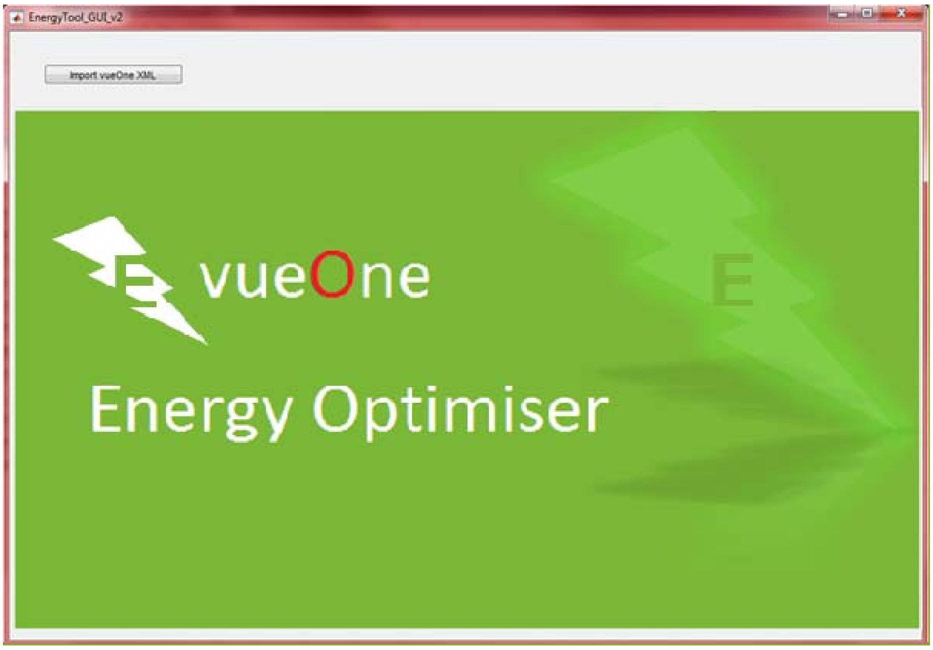


Figure 4.12: The Energy Optimiser tool front panel

Initially, the user is required to import the XML output file of a virtually modelled machine, this XML file can be generated from the vueOne tool. When clicking on the *Import vueOne XML* push button, a popup window shows the existing files on the user computer and asks to select the XML file.

After selecting the XML file, the front panel disappears and the main tabs appears. The number of the main tabs is equal to the number of actuators that are modelled in the vueOne tool, and the main tabs' titles have the same actuators' names in vueOne tool. In addition to actuators tabs, *Base actuators* and *System energy* main tabs are also created. Figure 4.13 shows the main tabs that are automatically created according to the corresponding actuating components of the vueOne model. Sub-tabs for each main actuating component tab are also created.

In each sub-tab there are fields, menus, and tables required to be filled or edited in order to enable the Energy Optimiser tool to predict the energy consumption of each component and then the modelled machine. This information, which is not defined in the current vueOne editor tools, describes some physical attributes and the operating conditions of each component that are necessary to predict the energy consumption.

In the *Application & move details* sub-tab, the imported data from the XML file specifies each actuator's: 1) number of moves, 2) the stroke covered per move, 3) the duration of each move, and 4) the start time of each move. Also, the user is required to select the *Application type* and fill *Load* and *Mode* columns of the moves table.

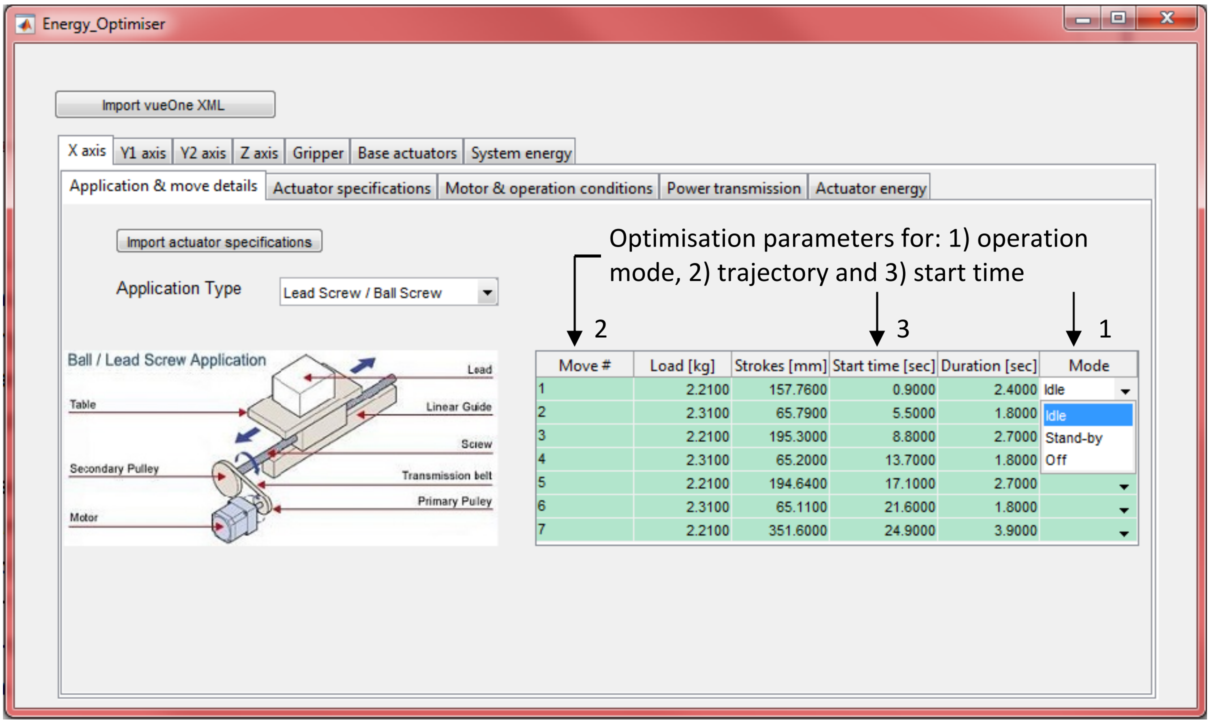


Figure 4.13: The Energy Optimiser main tabs and sub-tabs

The user can always save the actuator specifications, which he/she completed, for future use by clicking on the *Save actuator specifications* push button that exists in the last *Actuator energy* sub-tab. These specifications are then saved in the CSV format.

In the case of already saved specifications, the user can import them, by clicking on the *Import actuator specifications* push button that exists in the first *Application & move details* sub-tab. Then, a popup window shows the contents of the user computer to select the already saved CSV sheet, which in turn fills automatically the required data in all sub-tabs of this actuating component.

In the *Actuator energy* sub-tab, clicking on the *Import actuator CSV measurements* push button stores the actual energy consumption of this actuator to be represented in textual and graphical formats along with predicted results. These results can be generated by clicking on the *Actuator energy consumption* push button, as shown in figure 4.17 for the X axis energy consumption.

Figures 4.14 to 4.17 show the sub-tabs of the *X axis* main tab. It can be noted that the fields are filled, by the user, with the required energy related data of the X axis.

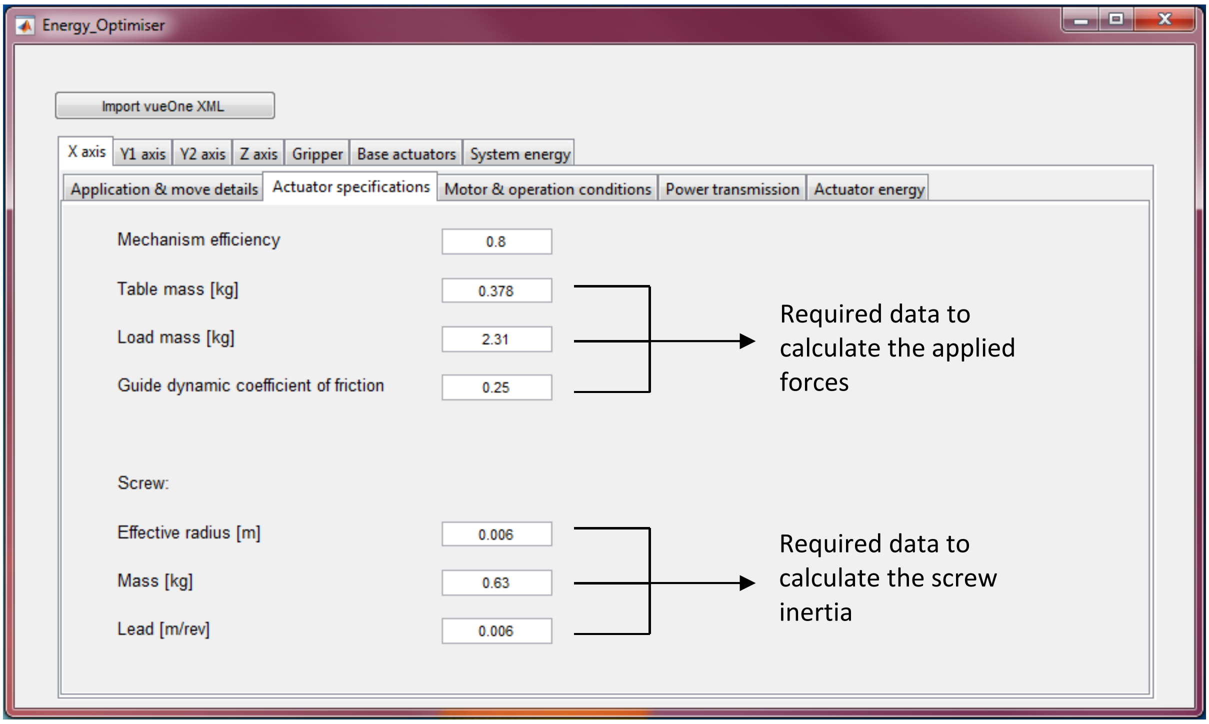


Figure 4.14: The Actuator specification sub-tab

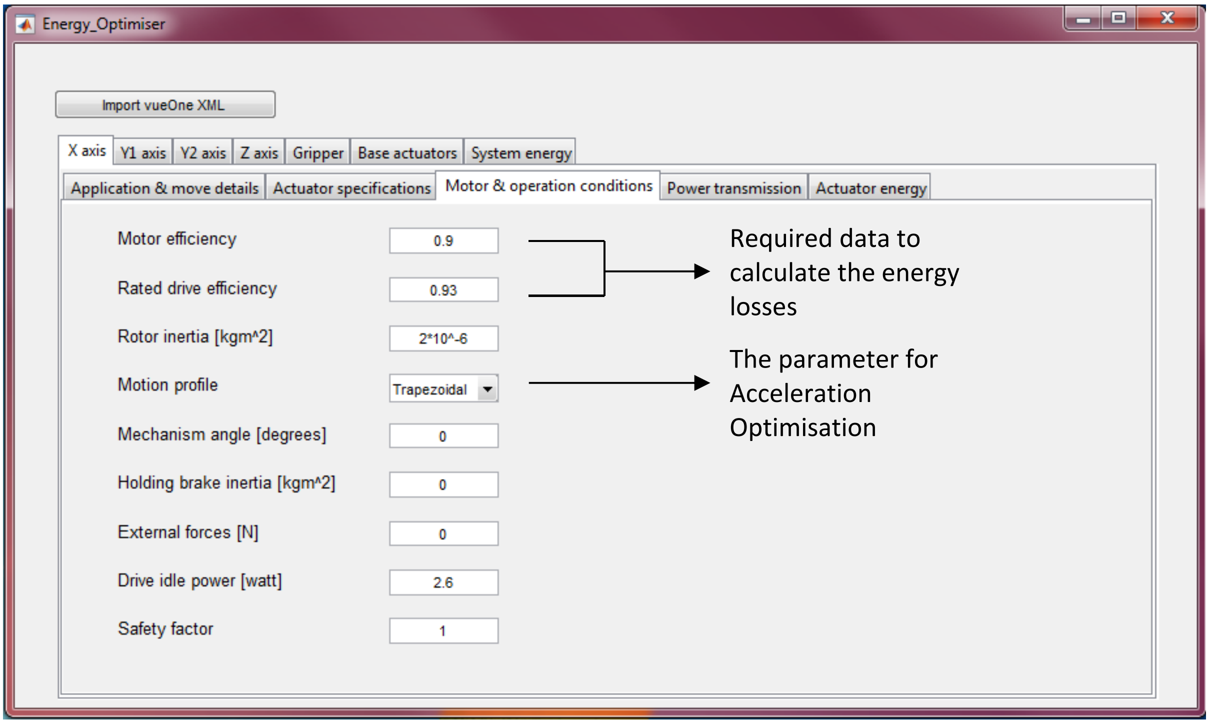


Figure 4.15: The Motor & operation conditions sub-tab

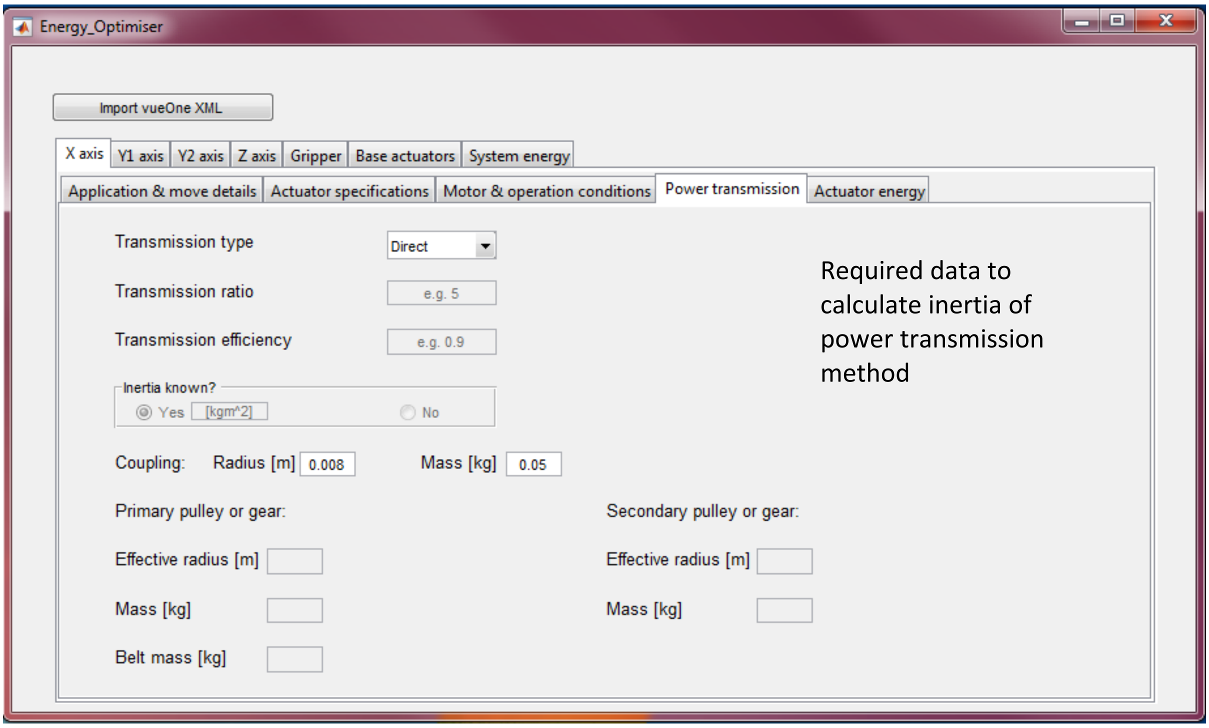


Figure 4.16: The Power transmission sub-tab

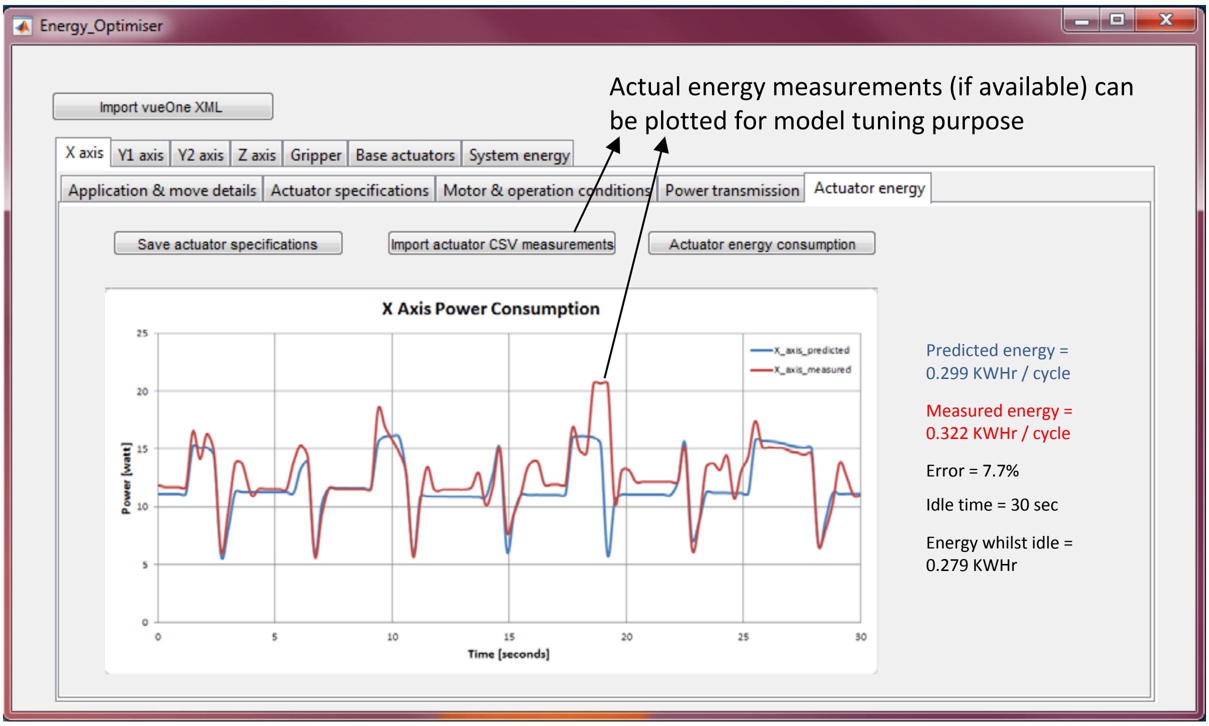


Figure 4.17: The X axis Actuator energy sub-tab

4.4.1 STATION 4 CASE STUDY AS AN EXAMPLE

Table 4.2 summarises the energy consumption data that was predicted by the Energy Optimiser tool for station 4 different actuators. The X axis energy consumption is shown in figure 4.17. From this table, it can be noted that the energy prediction error of Z axis is relatively high. The reason behind this is that the higher number of moves (12 moves) performed by this component comparing to other components (X axis performs 7 moves, Y axes perform 2 moves each, and the gripper opens and closes 6 times), which makes the accumulated error of all moves performed by this component is high.

Table 4.2: Energy consumption by individual component of station 4

Actuator	Predicted energy / cycle [KWHr]	Measured energy / cycle [KWHr]	Error	Idle time [seconds]	Energy whilst idle [KWHr]
X axis	0.299	0.322	7.7%	30	0.279
Y1 axis	0.254	0.261	2.8%	30	0.262
Y2 axis	0.276	0.288	4.3%	30	0.278
Z axis	0.394	0.446	13.2%	30	0.420
Gripper	0.200	0.192	4.2%	30	0.196

Since the *Base* energy consumers (such as the HMI screen, oil pump, ventilation fan, PLC power supply, etc.) consume constant amounts of energy according to their datasheets, the user is required to input these straightforward energy figures manually in *Base actuators* main tab. First, by specifying the number of these components, and then a table will be created automatically to be filled as shown in figure 4.18.

In this case study, there are three *Base* energy consumers; HMI screen, AC to DC power converter and PLC power supply:

1. The HMI screen is to show the station mimic and status during the operation and stand-by modes, also it enables the operator to select the manual or the automatic operation modes.
2. For this small station with simple tasks, the machine builder and the automation supplier had decided to use DC actuators, because they are easier to control and relatively cheaper than AC actuators. Thus, converting the main AC power into DC power is done by AC/DC power converter.
3. The PLC power supply provides power to PLC processing unit as well as inputs/outputs and interface modules.

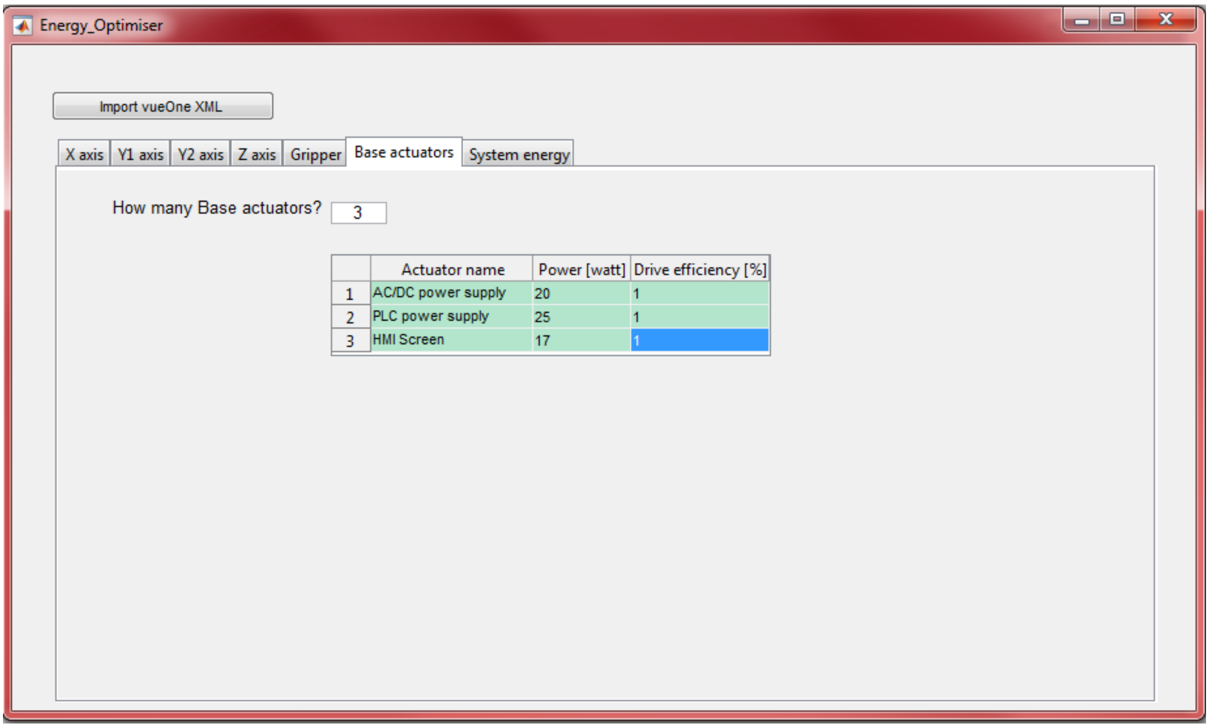


Figure 4.18: The Base actuators main tab

Finally, in the *System energy* tab, clicking on the *Import system CSV measurements* push button stores the actual energy consumption by the whole system (or machine). This data then can be represented in textual and graphical formats, along with the predicted results of the modelled system. This can be done by clicking on the *System energy consumption* push button. Figure 4.19 shows the predicted against the measured energy consumption by the whole station 4.

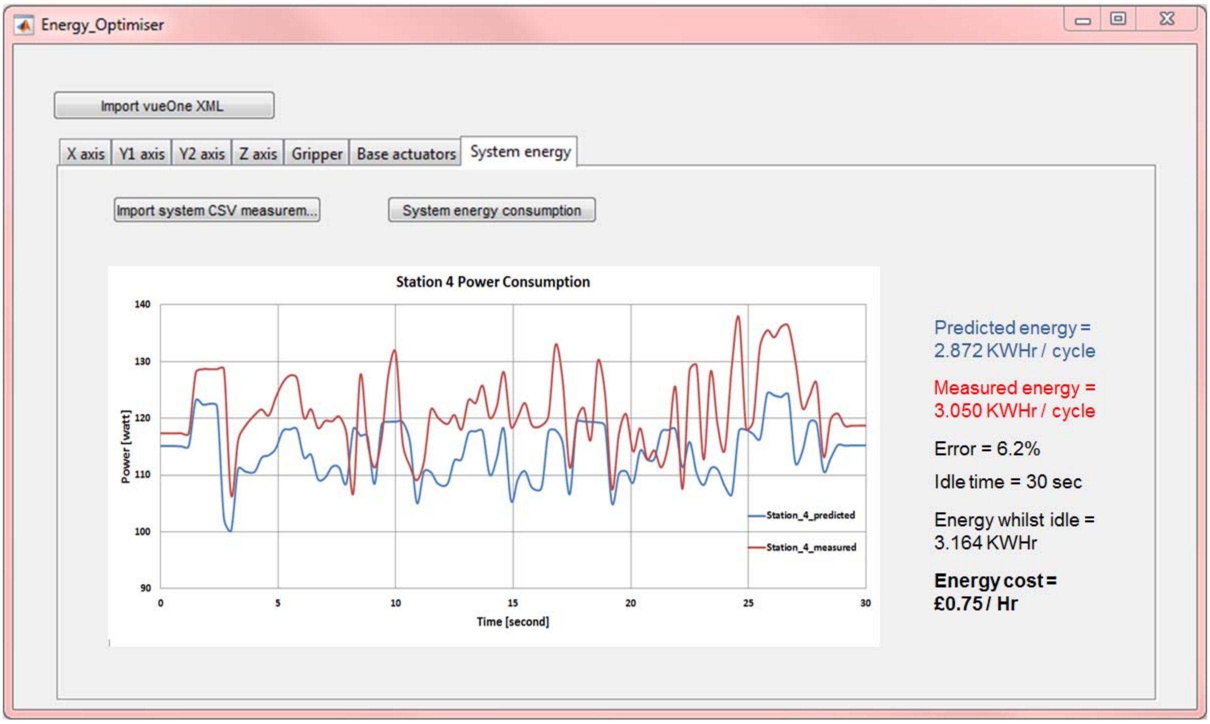


Figure 4.19: The System energy tab

4.5 RESULTS AND EVALUATION

4.5.1 DISCREPANCIES BETWEEN MEASURED AND PREDICTED RESULTS

As shown in figure 4.19, the predicted and actual energy consumption of the Pick-and-Place station were 93.8% the same. The aging and wearing factors of any component are excluded, since this station has been recently built and is only operated occasionally.

The resulting 6.2% difference can be explained as a result of one or all the following reasons:

1. The measuring device resolution, which stores power reading every 0.333 seconds, knowing that the finer the device resolution the more accurate readings can be captured.
2. Some of the user inputs in previous tabs and sub-tabs during specifying each actuator are estimated to a certain extent, because the lack of information provided by the manufacturer (SMC Corporation), such as the motor and controller efficiency of all actuators, and the inertia of some components' parts.
3. The unpredictable disturbances due to the transients between moving and standstill states of the actuators. These transients can take two forms: impulsive and oscillatory, as clearly appear in previous and next measurement charts.
4. The unforeseen interaction between different components.

However, using these empirical values and tests to calibrate and scale the predicted results is very useful measure. These values factorised in order to relate the realistic energy consumption to the predicted one, and then to the store the calibrated components in the library for future use. Thus, the manufacturers and machine builders can accurately predict the energy consumption by any of their calibrated component at the design phase of their assembly machine.

4.5.2 BASE COMPONENTS CONSUMPTION IS RELATIVELY HIGH

As can be observed from figure 4.18, the sum of the *Base* energy consumption is low, but comparing to the station small actuators' average consumption over the cycle time, one can observe these are almost equals. This fact explains the limited impact of optimising individual component on the whole station consumption. For example, altering the original motion settings of the X axis by more efficient motion profile saves 13% of this axis energy consumption, but this saving percentage becomes 1.5% considering the whole station consumption.

Therefore, in order to achieve higher energy saving in such small machines where the *Base* and *Ready* energy consumers consume approximately the same amount of energy, all the involved components are required to be optimised.

It is useful to mention that, the aforementioned *Base* consumers, particularly the HMI screen and the PLC power supply that are installed on station 4, can normally be found in much larger machines. The *Ready* actuators of these larger machines, consume much more energy than these *Base* components. Thus, optimising even one *Ready* actuator is expected to have clearer impact on the whole machine consumption. Furthermore, in the case of big *Base* consumers, they have to be operated efficiently by using motor inverters.

4.5.3 COMPONENT OPTIMISATION (CO)

As shown in figure 4.19, the cycle time of the SMC station to pick and place three lids on the top of three battery stacks is 30 seconds. The station then remains idle without any means of saving energy waiting for the next pallet, this idle time is also 30 seconds. Assuming that the kilo-watt-hour energy price is £0.12 day time, then the electricity cost for this simple with small motors (the biggest motor rated power less than 0.75 kilo-watt), and small loads (lid weight is about 0.1 kg) is £0.75 per working hour without applying any optimisation method. As will be explained later in the Summary section 4.6, this cost could be considerably reduced as a result of best practices. The following sub-section explains the implementation of the energy optimisation methods described in Chapter 2 and Chapter 3 of this thesis.

4.5.3.1 Acceleration Optimisation

- Identical trapezoidal velocity profile for all moves

The original velocity profiles for all the moves performed by the X axis actuator follow the trapezoidal velocity profile, but with same acceleration/deceleration and velocity values regardless the stroke and the move time. This method of defining the moves' profiles results different trapezoidal velocity profiles for different moves. This was done by keeping the same acceleration / deceleration values as 2000 mm/sec^2, and the constant velocity values as 125 mm/sec as shown in figure 4.22. The screenshot was taken from the X axis controller software that is developed by SMC Corporation.

The result of this design is a very high acceleration required in a very short time. Thus, high torque is developed by the axis motor to accelerate the load until reaching the constant velocity region. Then, the load moves in this constant speed for relatively very long time, before starting decelerating, again in a very short time. Consequently, the energy consumption by the motor that follows this kind of velocity profile is high.

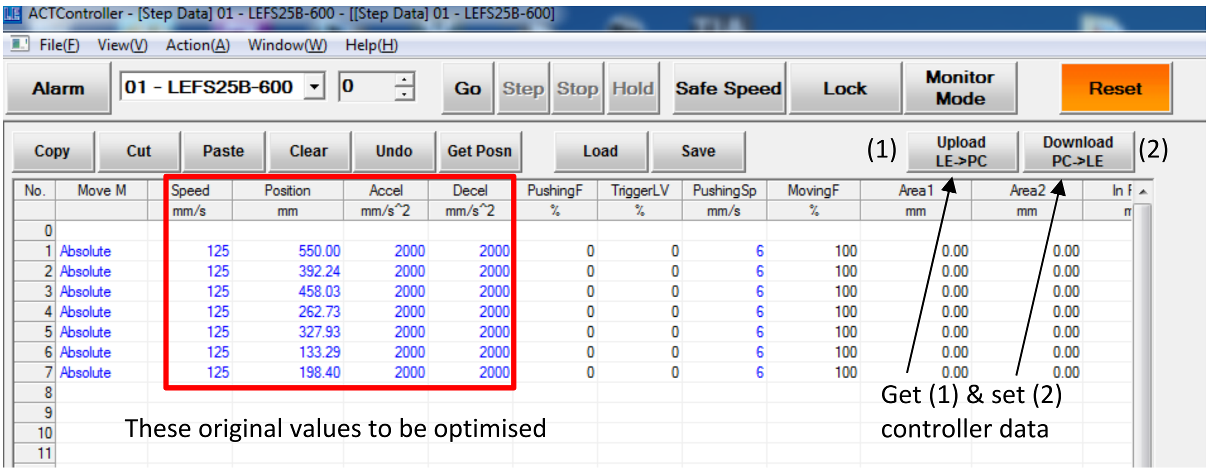


Figure 4.20: The Original motion data of the X axis as appears in the SMC controller software

Based on the above configuration, the time for each move has been calculated to be used as it is for the proposed new profiles. The Trapezoidal velocity profiles taking in account the time and distance for all moves follow the same pattern:

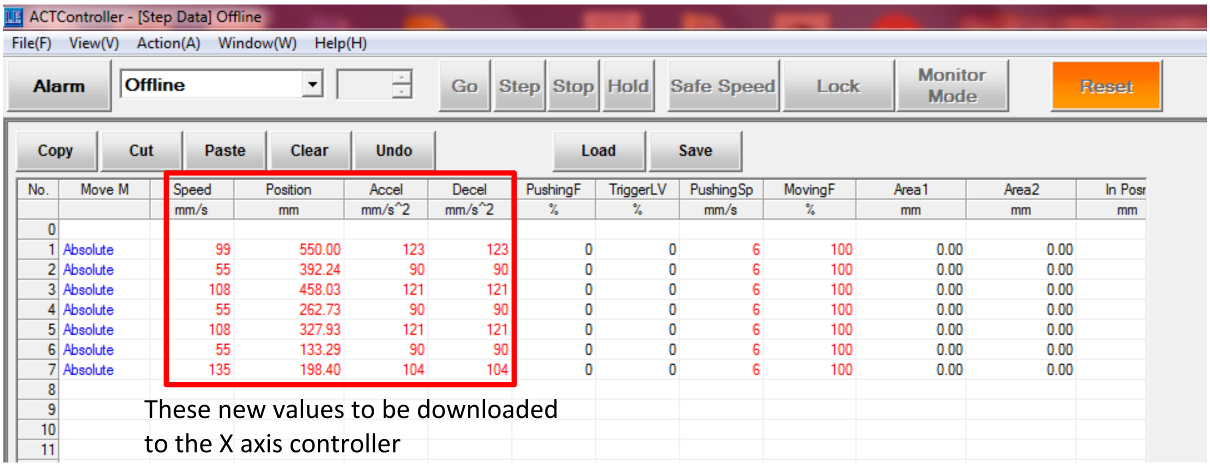
$$t_{acc} = t_{dec} = t_{cnst} = t_{tot}/3$$

Where: t_{acc} is the acceleration time, t_{dec} is the deceleration time, t_{cnst} the constant velocity time, and t_{tot} the total move time that is exactly the same in the original move configuration. And

$$d_{acc} = d_{dec} = d_{tot}/4, d_{cnst} = d_{tot}/2$$

Where: d_{acc} is the acceleration distance, d_{dec} is the deceleration distance, d_{cnst} the constant velocity distance, and d_{tot} the total move distance.

To configure the actuator movements according to this specific trapezoidal profile in the Energy Optimiser tool, the user is required to select the *Trapezoidal* motion profile in the *Motor & operation conditions* sub-tab shown in figure 4.15. Figure 4.21 shows the suggested new velocity and acceleration/deceleration values for the X axis controller.



No.	Move M	Speed mm/s	Position mm	Accel mm/s^2	Decel mm/s^2	PushingF %	TriggerLV %	PushingSp mm/s	MovingF %	Area1 mm	Area2 mm	In Posi mm
0												
1	Absolute	99	550.00	123	123	0	0	6	100	0.00	0.00	
2	Absolute	55	392.24	90	90	0	0	6	100	0.00	0.00	
3	Absolute	108	458.03	121	121	0	0	6	100	0.00	0.00	
4	Absolute	55	262.73	90	90	0	0	6	100	0.00	0.00	
5	Absolute	108	327.93	121	121	0	0	6	100	0.00	0.00	
6	Absolute	55	133.29	90	90	0	0	6	100	0.00	0.00	
7	Absolute	135	198.40	104	104	0	0	6	100	0.00	0.00	
8												
9												
10												
11												

Figure 4.21: The Trapezoidal motion data of the X axis in the SMC controller software

Reconfiguring the controller of the X axis to make its 7 moves follow the same proposed velocity profile has resulted in a saving of 11.18% against the original moves that follow different trapezoidal profiles. The result of the X axis with new moves is shown in figure 4.22.

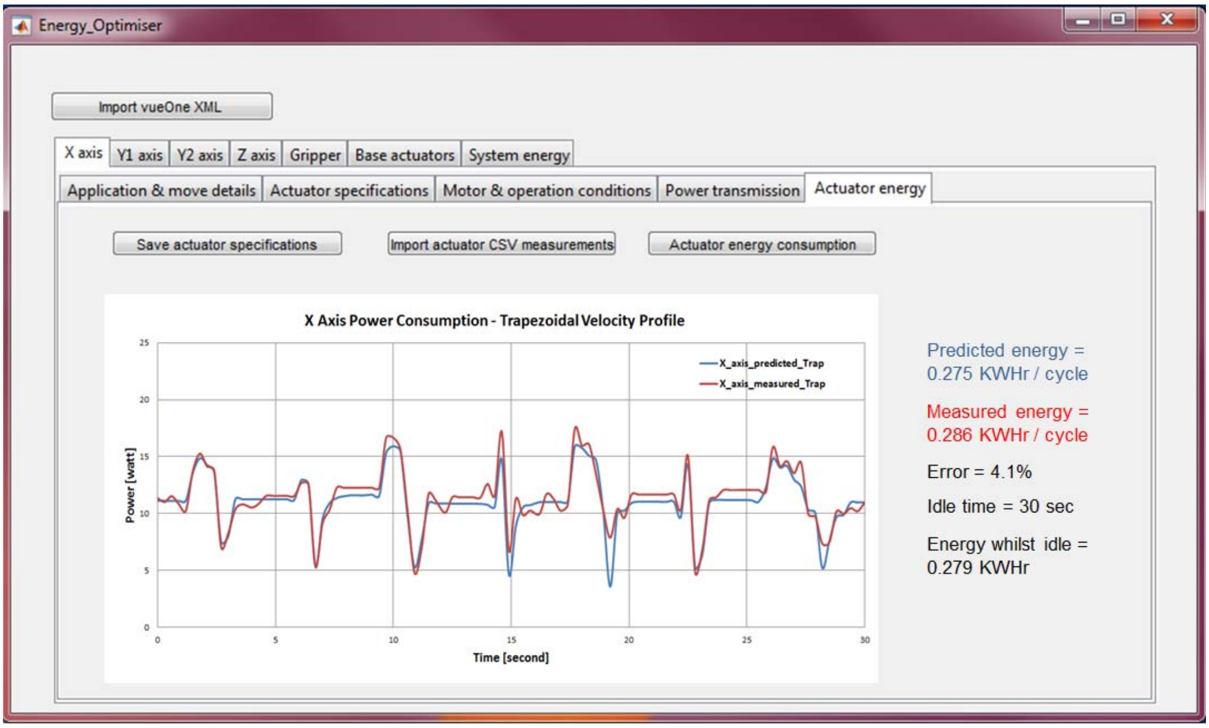


Figure 4.22: The X axis energy consumption under optimised trapezoidal motion profile

- Triangular velocity profile

Triangular motion profile is used in simple applications where the controller hardware does not support the trapezoidal or the s-curve motion profiles. It can also be used where the smoothness of actuator moves is not considered, which a big disadvantage of such velocity profile is. Since the values of the jerk (derivative of the acceleration/deceleration that causes the vibration of a moving actuator) reaches very high levels under the triangular velocity profile, thus, damage and wearing of mechanical parts can occur earlier.

In terms of energy consumption, the actuators that move according to this motion profile consume more energy than the actuators that move according to other velocity profiles such as the trapezoidal and the s-curve. The high energy consumption associated with the triangular motion is because the actuator keeps accelerating the load till it reaches a specific point, then immediately the deceleration part of the move starts without any involvement of constant velocity. This continuous acceleration/deceleration requires the actuator to develop a torque that can accelerate/decelerate the load, and overcome the resultant force of weight, friction and any other external forces. On the other hand, other profiles have a period for constant velocity that results of developing a torque by the actuator to only overcome the aforementioned forces without the need to accelerate the load.

The suggested triangular velocity profile of all X axis moves have been designed based on the following rules:

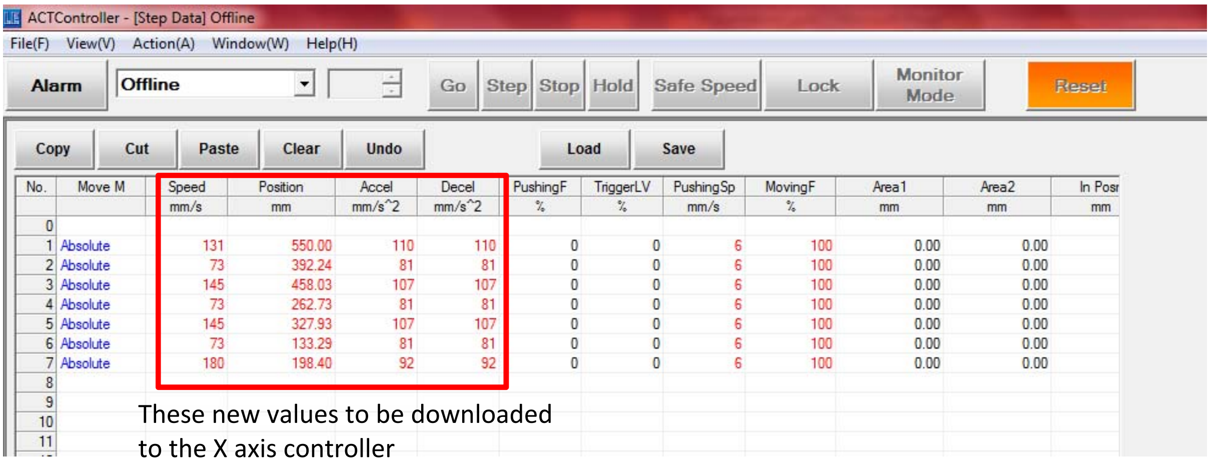
$$t_{acc} = t_{dec} = t_{tot}/2, t_{cnst} = 0$$

Where: t_{acc} is the acceleration time, t_{dec} is the deceleration time, t_{cnst} is the constant velocity time, and t_{tot} is the total move time. And

$$d_{acc} = d_{dec} = d_{tot}/2, d_{cnst} = 0$$

Where: d_{acc} is the acceleration distance, d_{dec} is the deceleration distance, d_{cnst} the constant velocity distance, and d_{tot} the total move distance.

To configure the actuator moves according to this triangular profile in the Energy Optimiser tool, the user is required to select the desired profile by selecting *Triangular* motion profile in the *Motor & operation conditions* sub-tab shown in figure 4.15. Figure 4.23 below shows the suggested new velocity and acceleration/deceleration values entered to X axis controller software.



No.	Move M	Speed mm/s	Position mm	Accel mm/s^2	Decel mm/s^2	PushingF %	TriggerLV %	PushingSp mm/s	MovingF %	Area1 mm	Area2 mm	In Posn mm
0												
1	Absolute	131	550.00	110	110	0	0	6	100	0.00	0.00	
2	Absolute	73	392.24	81	81	0	0	6	100	0.00	0.00	
3	Absolute	145	458.03	107	107	0	0	6	100	0.00	0.00	
4	Absolute	73	262.73	81	81	0	0	6	100	0.00	0.00	
5	Absolute	145	327.93	107	107	0	0	6	100	0.00	0.00	
6	Absolute	73	133.29	81	81	0	0	6	100	0.00	0.00	
7	Absolute	180	198.40	92	92	0	0	6	100	0.00	0.00	
8												
9												
10												
11												

Figure 4.23: The Triangular motion data of the X axis in the SMC controller software

Reconfiguring the controller of the X axis to make its 7 moves follow the suggested triangular velocity profile has resulted in consuming 17.7% more energy against the original moves, and 27.88% more of the proposed trapezoidal profile. Figure 4.24 shows the X axis energy consumption while its moves follow the triangular motion profile.

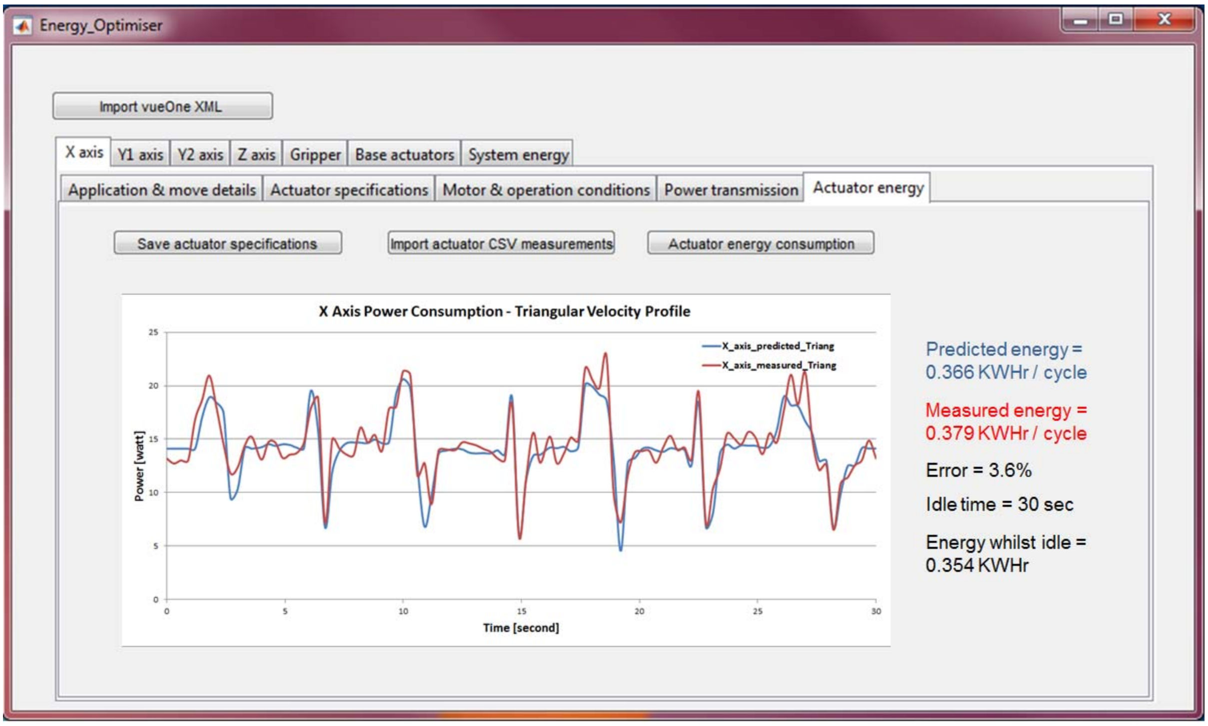


Figure 4.24: The X axis energy consumption under the triangular motion profile

4.5.3.2 Idle Time Optimisation

It has been observed that Y_1 and Y_2 axes consume 2.6 watt when the whole station is in stand-by mode, whereas when they become ready to operate (by pressing on the station's physical Start push button) Y_1 and Y_2 axes consume 10.4 watt and 11.1 watt respectively whilst both are idle for relatively long time as illustrated in figure 4.25 below. Therefore, the PLC code of the station has been modified to switch both Y axes into stand-by mode instead of being idle and consuming more energy.

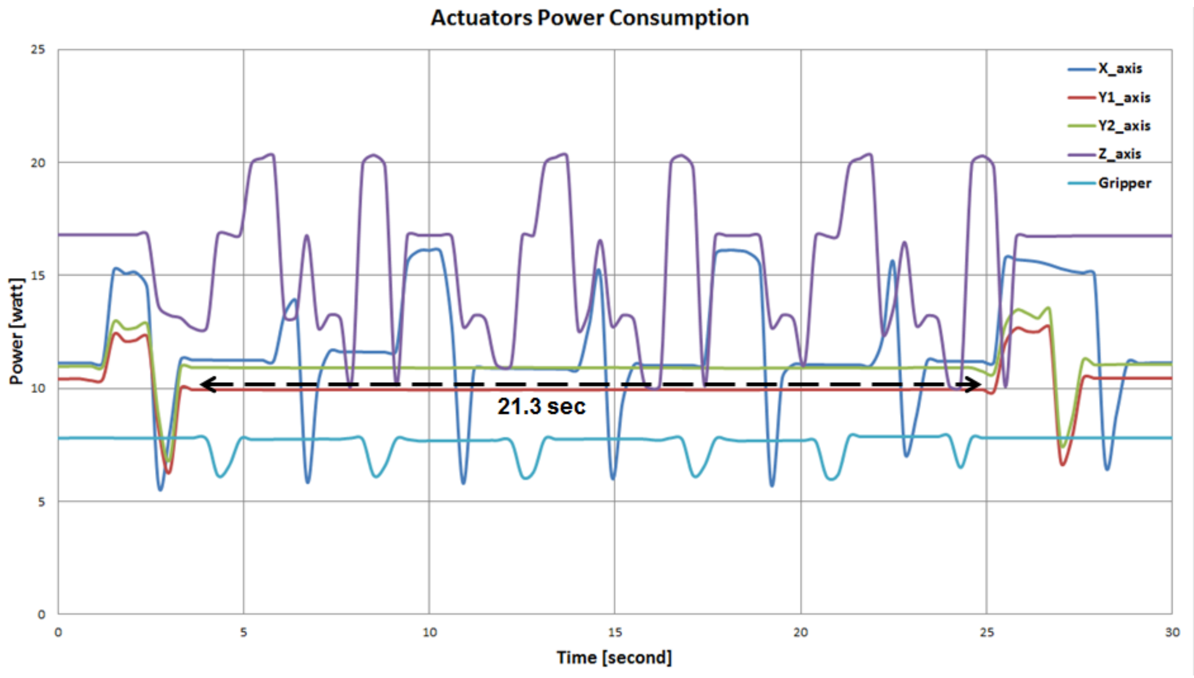


Figure 4.25: *Ready* components energy consumption

The screenshot in figure 4.26 shows the modified PLC program of station 4 to adopt the suggested stand-by modes for the Y_1 and Y_2 axes. A predefined flag M1000 (with label 2YON, and initial value = 1) has been inserted as a pre-condition in the same PLC network of Servo Control function block. This network allows the control signal of both Y axes controllers to be generated, and then the Y axes motors become energised and ready to operate. The pre-condition, 2YON, is controlled from the Sequence function block by the same conditions that required sending the Move Request signal to both Y axes controllers.

2YON flag is set (or latched) to be true as a pre-condition at the beginning of the Sequence function block. Then after 1 second of completing the first move by both Y axes, the flag goes off (or reset/unlatched) in the following rung, which makes it a false pre-condition. Consequently, the control signal to turn on both Y axes motors will not be generated until 1 second is remained before the second moves for both axes are due.

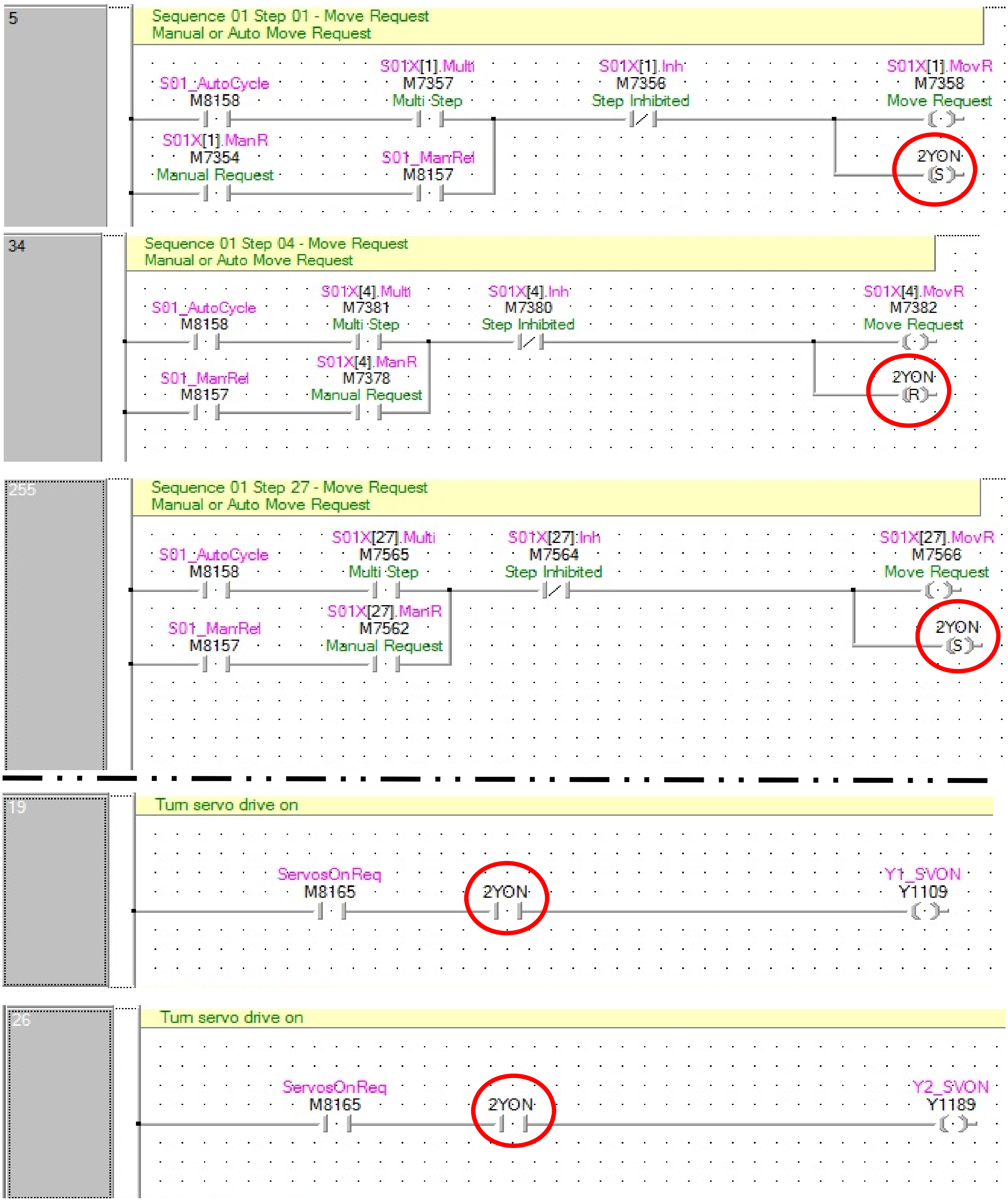


Figure 4.26: The station 4 PLC networks that are responsible for switching Y axes into stand-by mode

Switching components into different modes in the Energy Optimiser tool can be achieved by selecting the desired mode (*idle, stand-by* or *off*) in the *Application & move details* sub-tab as shown in figure 4.13. The *Off* mode reduces the energy consumption to zero for that specific actuator during that specific time between moves. Whereas, the *Stand-by* mode reduces the energy consumption in this case to 25% (a suggested percentage by author) of the previous move energy consumption to be consumed during that specific time between two subsequent moves. The new power values are considered when clicking *Save actuator specifications* or *Actuator energy consumption* push buttons in sub-tab *Actuator energy*.

Modifying the PLC program of station 4 to enable stand-by mode for both Y axes have resulted in 44.7% and 46.6% savings in Y_1 and Y_2 energy consumption, respectively, against the original idle state of both axes. Figures 4.27 and 4.28 show the results of Y_1 and Y_2 energy consumption after applying the new Stand-by mode to the Y axes.

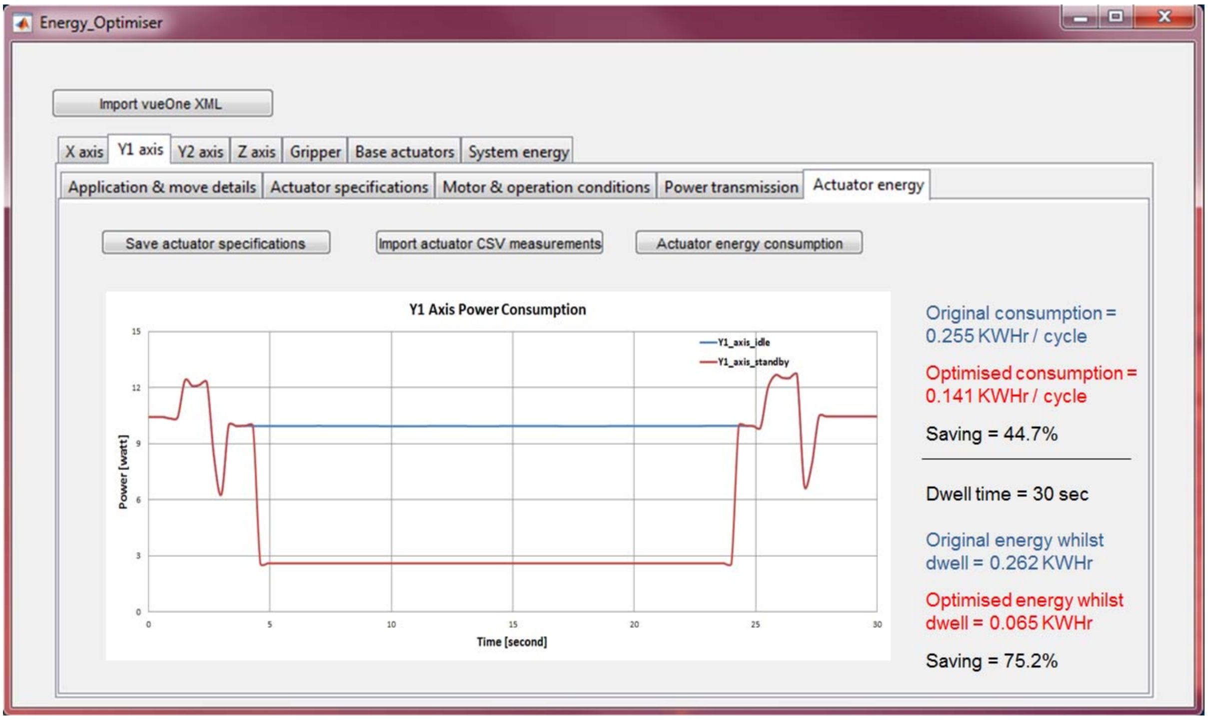


Figure 4.27: The Y_1 axis energy consumption in the case of idle and stand-by modes

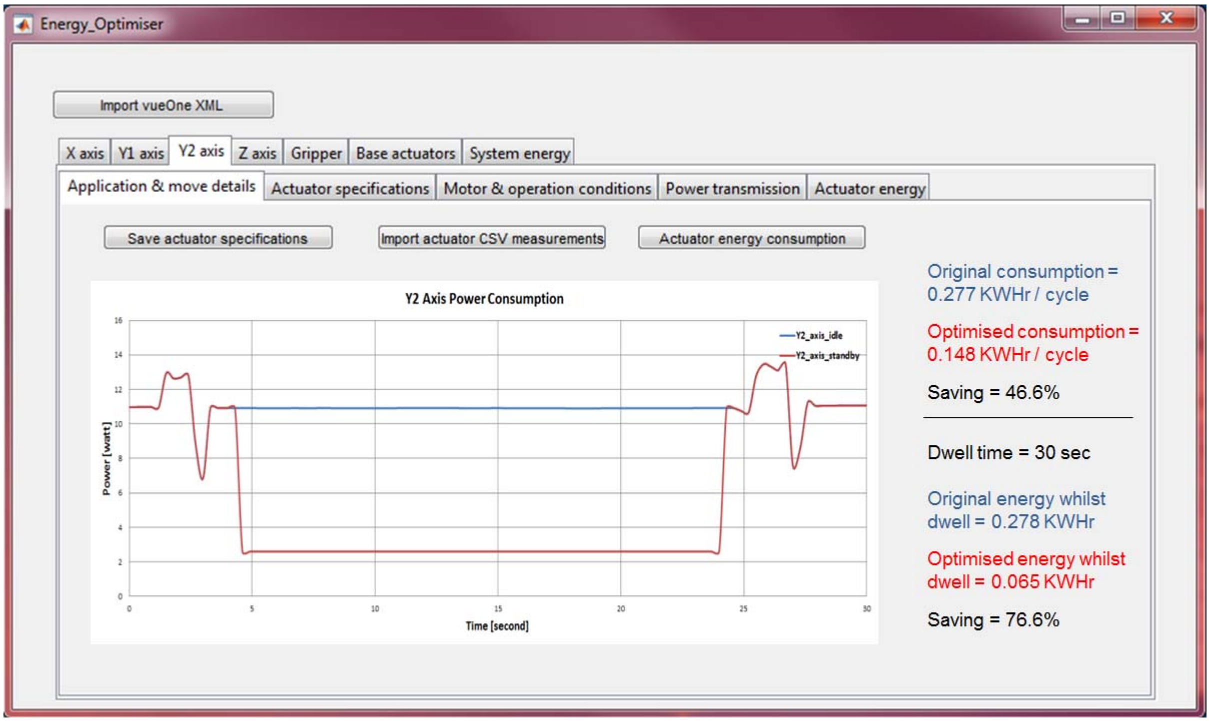


Figure 4.28: The Y_2 axis energy consumption in the case of idle and stand-by modes

4.5.4 SEQUENCE OF OPERATION OPTIMISATION

4.5.4.1 Trajectory Optimisation

A number of constraints have been taken in to account when the experiments were designed as explained in sub-sections 4.3.1 and 4.3.2. One of them is to keep the cycle time unchanged, because any change on the station cycle time will have an impact on the whole production line.

However, varying machine cycle time affects the amount of energy consumption. In an assembly line, a trade-off between machine's energy consumption and its throughput needs to be made based on many factors such as required production rate and operational cost. Generally speaking, if the considered machine within an assembly line is normally starved or blocked due to the other machines then increasing its cycle time (i.e. increasing operations times to transport the work-piece) will save energy without any bad impact on the overall throughput of the line. On the contrary, if the machine is blocking or starving other machines then decreasing its cycle time by decreasing non-critical operations times (e.g. going back to home position) will improve its throughput but the energy consumption will increase. These options can be considered during the design phase by virtually modelling the assembly line and then investigating the different SOO alternative designs.

One interesting trajectory would be moving the X axis first then both Y axes within the same original time of these movements together. This change requires high acceleration/deceleration and velocity values that are beyond the physical capabilities of the axes' controllers.

Due to the nature of how this station mechanical structure has been built, and the cycle time constraint, there is only one way to change the trajectory; that is by changing the sequence of picking and placing of the lids (e.g. instead of picking the first lid and place it on top of the first battery stack and so on, the gripper has to pick the second lid and place it on the top of the third stack and so on). The new suggested sequence requires changing only the X axis target positions as shown on figure 4.29. This kind of changing the trajectory can be achieved in the Energy Optimiser tool by editing the rows contents of the table in the *Application & move details* sub-tab of the X axis shown in figure 4.13. However, the resultant energy consumption by X axis is less than 3% comparing to the original trajectory energy consumption.

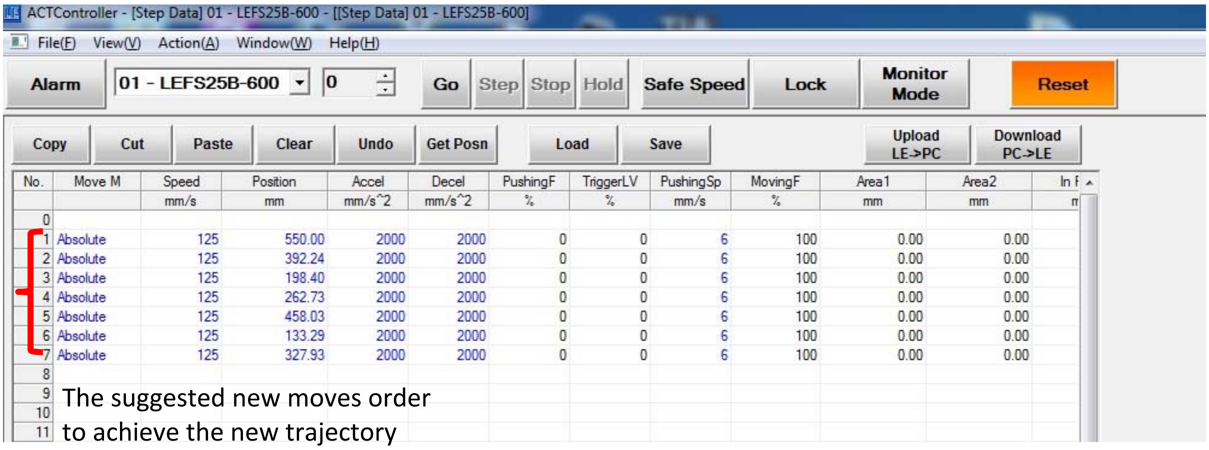


Figure 4.29: X axis position rearranged in order to produce new station trajectory

4.5.4.2Starting Time Optimisation

Introducing time offset between the X axis and both Y axes is required in order to prevent them from starting their moves at the same time. Generally, spikes in power demand can cause system malfunctions, as well as extra costs and fines if the electric power exceeds a certain threshold. Therefore, electric spikes are undesirable in any case and under any conditions.

As shown in figure 4.30, two peaks can be noticed as a result of the X, Y_1 and Y_2 starting to move at the same time in the first and last moves of the station. Hence, more energy is consumed at these times, and in bigger applications circuit breaker trip or even worse problems could occur if the peaks are too high.

The suggested change in station sequence is to start the X axis 0.9 seconds earlier than its original start time, and keep both Y axes to start normally together (they must move together, otherwise the X axis will be twisted, since its two ends are connected to both Y axes). Also, both Y axes are delayed by 1.2 seconds before starting their second and final move within station cycle time. This slight time shift between the X axis and both Y axes is expected to minimise the power demand peaks of the station.

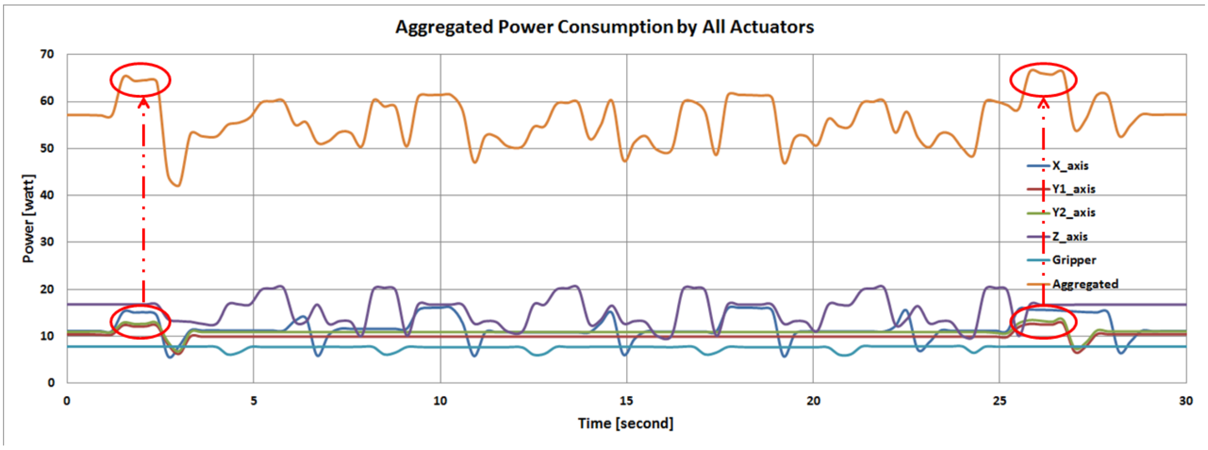


Figure 4.30: Peaks in power consumption of the actuating components because of the same starting time

PLC code modification is required to implement these two proposed time offsets. This modification is carried out by introducing an ON-delay timer contact in series with the *ServOnReq* contact in both rungs. These two rungs deliver the control signal from the station PLC to both Y axes controllers (*Y1SVON* and *Y2SVON,* which in turn switch on both motors) in Servo function block. Two timers of 1.2 seconds each were added in series with *ServOnReq* in the Servo function block. Figure 4.31 below shows the PLC rungs with the new timers.

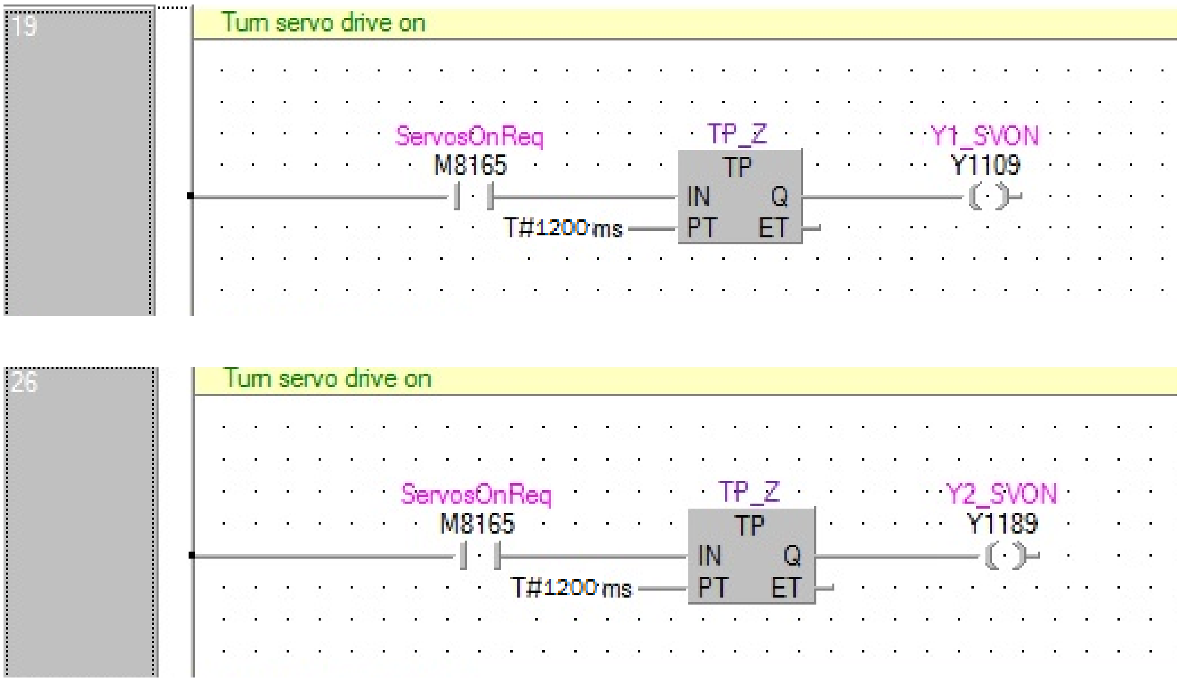


Figure 4.31: Station 4 PLC networks that are responsible for introducing the time offsets between axes

The suggested components offset can be done in the Energy Optimiser tool by editing the *Start Time* of the move in the table in *Application & move details* sub-tab of X, Y_1 and Y_2 actuators.

4.6 Summary

Energy optimisation methods at both component and machine levels are integrated effectively in a holistic framework, with good practice of energy prediction method that is described in the Chapter 2 and Chapter 3. Table 4.2 shows the predicted against the measured energy consumption of station 4 components, whereas table 4.3 shows different optimisation methods at component level, where good amount of energy saving has been achieved.

Table 4.3: Component optimisation results summary

Exp.	Axis	Optimisation Method	Result
A1	X	Acceleration Optimisation (Trapezoidal velocity profile)	**11.18% less** energy consumption than the original profile
A2	X	Acceleration Optimisation (Triangular velocity profile)	**17.7% more** energy consumption than the original profile

A3	Y1	Idle Time Optimisation (stand-by mode)	**44.7% less** energy consumption than the original idle state
A3	Y2	Acceleration Optimisation (stand-by mode)	**46.6% less** energy consumption than the original idle state
B1	X	Trajectory Optimisation (alternative order of pick and place positions)	**3% less** energy consumption than the original trajectory
B2	X, Y_1, Y_2	Start Time Optimisation	**4% less** energy consumption than the original trajectory

Figure 4.32 below shows the energy consumption of the whole station after applying all the aforementioned optimisation methods at both component and station levels, where: 1) both X and Z axes velocity profiles are reconfigured to consistent trapezoidal profiles, 2) both Y axes switched into stand-by instead of their idle states, and 3) time offset introduced between X axis and both Y axes during when they moved together. The result shows 27% energy saving against the original design of the station.

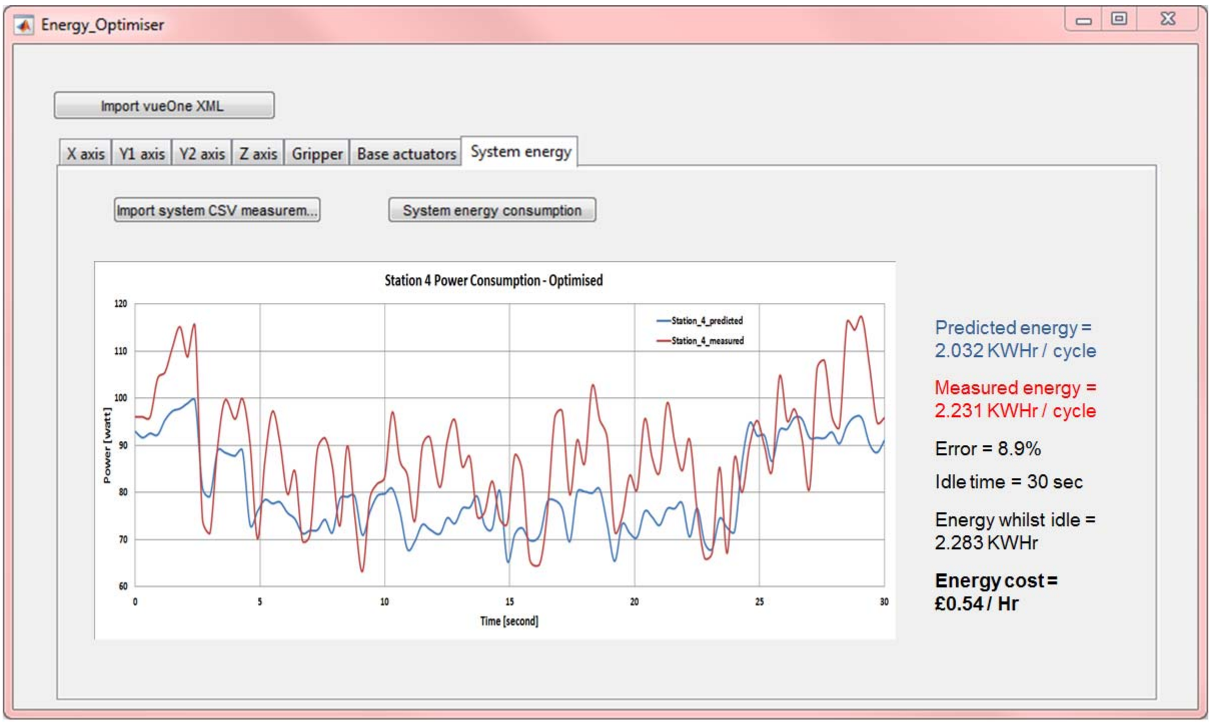


Figure 4.32: Optimised station 4 energy consumption

Different possible optimisation experiments were conducted on station 4. Other experiments could not be done because of different reasons such as: 1) the mechanical structure of the station which dictates limited trajectories to be investigated, and 2) the axes controllers' incompatibility to support the more energy efficient S-curve motion profiles, and 3) The axes controllers maximum velocity and acceleration capabilities.

The energy prediction and optimisation results, which were achieved by implementing the novel CBEO framework, has proven its validity and as a proactive, holistic and readily applicable framework. Moreover, the Energy Optimiser tool, which has been developed by the author as main contribution of this research, has proven its capabilities to provide high level of energy prediction, and help to optimise the virtually modelled machines in a user friendly manner. Also, the tool has proven its maturity to be fully integrated with the vueOne tool set in a new phase of work, or it can be used as standalone tool. However, many features still need to be added to the Energy Optimiser tool, mainly the ability to pull measured energy data over communication networks, to be better utilised in smart factory and cyber-physical system context as highlighted in sub-section 5.4.6.

Chapter 5

Conclusion and Future Work

This chapter concludes the research work reported in this thesis. A comprehensive summary of the research achievements, contributions and benefits are outlined. At the end, the recommendations for the future directions are given.

5.1 ACHEIVEMENTS OF RESEARCH OBJECTIVES

The aim of this research is to develop a comprehensive and proactive framework to predict and optimise the energy consumption of assembly systems throughout the lifecycle. The proposed CBEO framework facilitates the integration between component-based approach with currently non-coupled energy prediction and optimisation methods in a virtual engineering environment, in order to relate manufacturing process parameters with the next-generation sustainable manufacturing.

By providing this Component-Based Energy Optimisation (CBEO) framework, the author anticipates to promote best practices of manufacturing system efficiency, reuse, and modularity towards rapid responsiveness within the sustainable manufacturing domain. Number of research objectives are described in section 1.6 of this thesis to realise the aforementioned aim. This section highlights the achievements towards these objectives.

Objective 1: Examine and identify the common features of the existing approaches and practices to energy efficient manufacturing and their implementation and shortfalls.

An extensive review of the existing energy utilisation methods and practices within literature and industry is presented in Chapter 2, with particular emphasis of the automotive sector.

The limitations and shortfalls of current approaches' capabilities to serve in future sustainable manufacturing systems are discussed in section 2.2. Additionally, section 2.3 highlights the main drivers for more sustainable manufacturing. As discussed in section 2.5, it is established that the component-based reconfigurable manufacturing approach is a key element for extended development of different tools and methods to compensate for the current limitations.

Objective 2: Define suitable logical abstractions that are required to best address end-user requirements.

Regular discussions mainly with Ford Motor Company UK led to the development of a realistic and applicable energy prediction and optimisation concepts as stated in section 3.2. It is further concluded that any new approach for energy optimisation should fit within the established engineering workflow to maximise the industrial acceptability and compatibility.

Objective 3: Adopt an approach that supports the reuse of modular machine components for improved energy efficiency.

A level of granularity throughout the process of developing the new energy optimisation framework is presented in sections 3.4 and 3.5. The developed framework is a component-based, where each individual component includes a well-defined energy profile. Thus, combining these components to build larger systems, makes them reconfigurable to achieve the best energy efficiency performance. Generally, building a manufacturing system from energy optimised components at the design phase, is expected to lead to energy efficient processes and operations to be performed by this system at its operation phase.

Objective 4: Extend the capabilities of the existing vueOne VE tool to include the required energy related data of actuator components and machine operations in order to accurately predict and then optimise machine energy usage.

The existing features and characteristics of the vueOne virtual engineering tool are discussed in section 3.6, and the required enhancements from energy efficiency point of view are discussed in section 3.7. These enhancements to develop an accurate energy prediction and effective energy optimisation at the design and process planning phases require changes in the vueOne data structure and subsequently the user interface.

Objective 5: Develop a novel proactive, comprehensive and applicable energy prediction and optimisation framework to improve the efficiency of assembly machines throughout their lifecycle.

The novel energy optimisation CBEO framework is proposed, based on the established IMC theory, and presented in section 3.3. The difference between this proactive approach and currently implemented reactive approaches is also distinguished. Sub-section 3.3.1 explains how the proposed CBEO framework can be applied throughout the entire system lifecycle. The CBEO framework enables energy optimisation of any manufacturing system that is constructed from modular and optimised components, which are stored in the component library. Sections 3.4 and 3.5 summaries the procedure to build and configure energy optimised components before (re)using them to build an energy optimised system.

Objective 6: Develop a novel engineering tool for energy prediction and optimisation at the component and machine levels.

The Energy Optimiser tool has been developed by the author as a stand-alone tool to prove the capabilities of the proposed CBEO framework. Full integration of the tool with the existing vueOne toolset is expected to provide manufacturers and machine builders with better insights of system energy efficiency, and subsequently the operational costs at the design phase, where most benefits can be achieved with minimum cost, time, risk and disruption.

Objective 7: Implement a prototype system to validate the developed framework and its tool, hence the research objectives.

A case study of a real application is presented in Chapter 4. Using the developed Energy Optimiser tool, best possible energy efficient performance has been achieved on the SMC pick-and-place assembly station. The optimised control was compiled and downloaded to the SMC LECP6 motor controllers attached to the station axes, and the Mitsubishi MELSEC-L PLC station controller. The station was operated efficiently as explained in sections 4.5 and 4.6, thus validating the research hypothesis presented in section 1.5.

Based on the case study experiments, evaluation of the proposed CBEO framework has been carried out in Chapter 4 hence the benefits were revealed, including improving system reconfigurability and reusability as explained further in the next section 5.3.

5.2 RESEARCH CONTRIBUTIONS

This research makes the following original contributions to the field of manufacturing engineering of automotive systems, as well as the virtual engineering:

- A profound understanding of the current limitations that should be resolved, and the requirements that should be met in order to propose and design a capable framework for energy prediction and optimisation for industrial systems. This framework should use the virtual engineering tools throughout machine lifecycle [14].
- A proactive, applicable and comprehensive framework for energy prediction and optimisation within component-based virtual engineering tools that enables the implementation of verified control configurations [15].

- A systematic approach for generating energy efficient motion and control configurations based on the information provided by component-based virtual models of manufacturing systems, and utilising these components in an efficient way to deploy to physical systems [15].
- A comprehensive approach to classify machine components into different categories based on their energy consumption, including the idle energy losses [14].
- A comprehensive approach to maximise the energy optimisation of manufacturing systems by applying different optimisation methods at the component and machine levels [15].

5.3 RESEARCH BENEFITS

The case study and evaluation carried out in Chapter 4 highlighted a number of benefits of adopting the proposed CBEO framework for energy prediction and optimisation, below is an outline of these benefits:

5.3.1 INTEGRATED ENGINEERING OF CONTROL AND MANUFACTURING SYSTEMS

The Virtual Engineering (VE) is a key technology to enable energy prediction and optimisation prototype in this research, through the extension to the vueOne toolset. A single energy-efficient model can be deployed throughout the entire manufacturing system lifecycle. The component-based approach to manufacturing system design, coupled with associated virtual modelling and simulation tools provide an ideal basis for developing the next generation of energy optimisation tools, by focusing on the process and control modelling to implement an accurate and consistent energy prediction and optimisation capabilities.

5.3.2 DEPLOYMENT OF VIRTUALLY VERIFIED MOTION AND CONTROL CONFIGURATIONS

The CBEO framework benefits from the synergies between the Component-Based (CB) approach that utilises the Virtual Engineering (VE) environment with currently non-coupled, state-transition energy modelling, different energy optimisation methods, and the Energy Management Systems (EnMS) techniques, that are all formulated in the Internal-Model-Based Control (IMC) structure.

The case study has proven the capabilities of the CBEO framework by deploying the predicted, verified and energy-optimised component to physical assembly system. Alternative system designs and configurations can be examined and investigated in the same manner throughout system lifecycle.

5.3.3 INHERENT ENERGY PREDICTION AND OPTIMISATION OF TARGETED SYSTEMS

The closed-loop feedback IMC theory, on which the proposed CBEO framework is designed, ensures the discrepancy between the desired and actual energy consumption can be minimised under any operation conditions. This is because of the inherent IMC capabilities of reference targeting and disturbance elimination as long as the component library is updated. In the case of already established system, the designer is required to ensure that the component configurations and system control are adjusted and aligned with the component library.

5.3.4 SHORTEN THE REQUIRED TIME TO OPTIMISE SYSTEM ENERGY USAGE

As shown in sub-sections 4.5.3 and 4.5.4, investigating alternative energy optimisation opportunities of the targeted system using the Energy Optimiser tool to estimate the impact on system energy efficiency is time effective. Therefore, hardware and software improvements on the manufacturing system can be performed based on profound insight.

5.3.5 IMPROVE RECONFIGURABILITY

The evaluation of the case study in chapter 4 shows the impact of component energy consumption on the whole machine energy consumption. Also, reconfiguring an individual component has an impact on machine energy consumption. The information about reconfigured component is automatically evaluated and the results are represented at both component and system levels as shown in section 4.4 and 4.5.

5.3.6 IMPROVE REUSABILITY

As stated in sub-section 3.4.2 and shown in section 4.4, the verified component with its well-defined energy related data, can be easily retrieved and directly fills the required fields. These components reside in the component library can be always (re)used to investigate system energy consumption throughout its life cycle.

5.4 FUTURE RESEARCH DIRECTIONS

The work of research, which has been presented in this thesis so far, has provided the foundation to achieve the research objectives outlined in section 1.6. However, it is envisioned that further developments of the framework could be made by future research towards the following additional objectives.

5.4.1 TRANSFERRING ENERGY DATA OVER COMMUNICATION NETWORKS

For already established systems, importing measured energy data for both the component and system levels is currently being done manually. This requires a lot of time and effort to set up and wire the measurement devices, and then import the data manually. It is expected to more convenient and feasible to do the energy data transfer over a communication network. This approach is also more compatible with new trends of smart manufacturing such as Industry 4.0 and Cloud Manufacturing where a digital form of the actual system could be supported throughout its lifecycle.

5.4.2 AUTOMATIC MODIFICATION OF THE CONTROL CODES

As shown in sub-sections 4.5.3 and 4.5.4, currently the system designer is required to modify motor drive settings (speed and acceleration/deceleration, and moves order) and PLC code (set/reset actuating signals to motor drives, set timers to create offset between actuators starting times, and sequence of operation) manually. Since these tasks are relatively simple to do yet they have very huge impact on shortening the development time, therefore it is highly recommended to develop a smart way to modify drives settings and PLC codes automatically which also has the benefit of reducing the programming skills requirements.

5.4.3 ADD ENERGY-ORIENTED ACTUATORS SIZING FUNCTIONALITY

There would be a high added value for the virtual system to suggest at the design phase the closest available actuators. These suggested actuators are expected to perform the required tasks with the minimum energy consumption. The actuator database should be populated by actuators from relevant brands such as SMC, Festo, Bosch-Rexroth, etc.

Choosing the closest available actuators is important to prevent the waste of energy that is caused by actuators oversizing. It also reduces the purchasing and operational costs. Generally, an important reason for actuators oversizing is the uncertainty of load requirements [86], since this issue can be resolved in advance by using the proposed CBEO framework, then there is no justification for oversizing unless the machine designer wants to, due to a potential load increase, or commonality of drive sizes is seen as more important than its efficiency.

5.4.4 ROBOTIC SYSTEMS

Robots are widely used in the automotive industry for assembly and machining functions. Their energy consumption during point-to-point moves is highly dependent on their trajectories, moving joints acceleration and start time, and idle joints operation modes. This is exactly like other servo mechanisms (i.e. in the case study that is presented in Chapter 4).

Therefore, including robotic systems in the proposed CBEO framework and its Energy Optimiser tool seems to be reasonable and achievable. However, the interaction between the robot joints is expected to be greater than the interaction between the components of the ordinary servo-actuated machine.

5.4.5 PRODUCTION LINE ENERGY OPTIMISATION

Since improving the energy efficiency of stand-alone has been achieved by implementing the CBEO framework, the author believes that the natural development of this framework could be represented on a larger scale to include whole production lines and even whole manufacturing plants.

However, it is expected to be more complicated to optimise the energy consumption at production line level because of the larger number of involved factors; such as cycle time optimisation. Also, the interaction between different stations on the same production line; such as bottle neck minimisation and starving-blocking optimisation, have to be carefully considered.

5.4.6 INTEGRABILITY WITH INDUSTRY 4.0

The Industry 4.0 is a new industrial revolution initiative, which has successfully drawn the interests of leading automation suppliers and manufacturers, could be widely implemented in the next decade. A key aspect of this new revolution is that the Industry 4.0 aims at finding any inconsistency/defect in the manufacturing system in order to optimise it. From an energy perspective, this is exactly what has been done in this research.

A core principle of the Industry 4.0 is gathering the data about granulated components, and then share these data lively with other components/processes. The purpose of this is that to ensure the best knowledge is available in real time, and hence optimisation opportunities for these components/processes can be identified and realised.

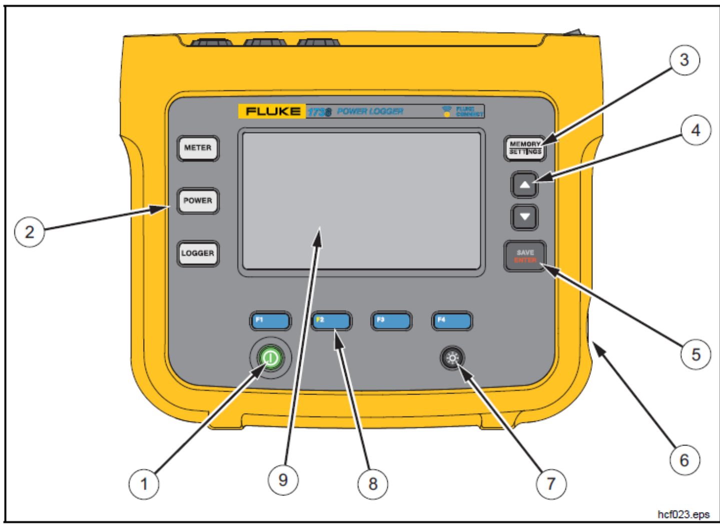
Suitable connectivity is needed for the reported research to be integrated from Industry 4.0 viewpoint. This can be achieved by, for example connecting the CBEO framework to motor controllers, PLC's and energy monitors by OPCUA (Open Platform Communications Unified Architecture) protocol, making automated adjustments in motor controllers settings, modifications to PLC code, and virtual component library updates and refinements is expected, much of this functionality is supported by enhancements to the vueOne toolset.

Bridging the gap between real component/system and its digital representation is important to make the energy data model is consistent with the real world. This can be achieved by collecting real time data of cyber-physical system's components (e.g. motor controllers, and energy monitors) during the operation phase in a structured manner. The collected data is to be mapped back to the initial design energy related data, in order to tune the components stored in the virtual component library. This is expected to make them (re)usable to support the energy prediction and optimisation of real manufacturing systems during their operation phase [43].

Appendix A

SET UP AND WIRING

- Fluke 1736 Setup

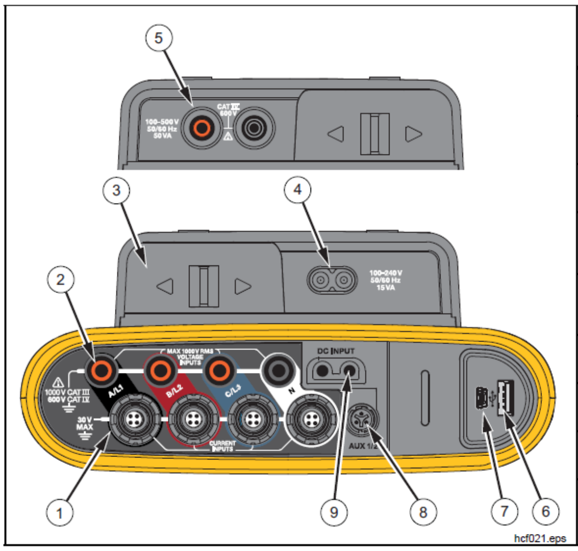


Item	Control	Description
1		Power on/off and status
2	METER POWER LOGGER	Meter, Power, or Logger function selection
3	MEMORY SETTINGS	Memory/Setup selection
4	▲▼	Cursor control
5	SAVE ENTER	Selection control
6	Kensington lock	
7		Backlight on/off
8	F1 F2 F3 F4	Softkey selection
9	Touch screen display	

Figure A.1: Fluke 1736 Portable Power Logger front screen

1. From *Instrument Settings* set up the language, date, time and currency
2. Back to main screen, press on *Change Configuration* then select *Energy Study* as a study type, *3-ph Wye* as a topology, *220 V* as nominal voltage*,* *50 Hz* as nominal frequency and *1:1* voltage ratio.
3. Press on *LOGGER* soft key and then press on *Edit Setup* on the touch screen to configure the logging session. Up and down soft keys used to adjust the logging duration to the smallest *10 minutes* as the cycle time of the station to be measured is less than that, and the smallest average logging time every *1 second*.
4. Finally, go back to *Logger Setup* menu, the device now is ready and when the wiring is completed press *Start Logging*.

- Fluke 1736 Wiring



Item	Description
①	Current measurement inputs (3 phases + N)
②	Voltage measurement inputs (3 phases + N)
③	Power Cord/Measurement Line Slide-Cover
④	Power Cord AC Input 100-240 V 50/60 Hz 15 VA
⑤	Measurement Line AC Input 100-500 V 50/60 Hz 50 VA
⑥	USB connector
⑦	Mini-USB connector
⑧	Aux 1/2 Connector
⑨	DC Power Input

Figure A.2: Fluke 1736 Portable Power Logger connection ports

1. Make sure the battery is charged enough, otherwise connect the power cord input (item 4) into main, or connect it directly to the circuit being measured via line AC input (item 5).
2. Encircle the 3-phase and neutral conductors, connected to the outputs of station 4 main circuit breaker, by the 4 AC current clamp probes.
3. Connect the AC clamp probes into Fluke 1736 to current inputs (item 1).
4. Connect 4 magnetic probes for each one of 4 voltage leads (including the lead for neutral). Then connect the voltage leads into Fluke 1736 to AC voltage inputs (item 2)
5. Put magnet probes on the screws of the outputs of station 4 main circuit breaker.

- Voltech PM6000 Setup

1. By pressing on *CONFIG* within *System* group, date and time were adjusted.
2. When PM6000 is switched on and within *Display* key group, *GRAPH* key was pressed and the required channels 1 – 5, their tables and graphs were shown on the display.
3. *DC wiring* was selected for channels 1 – 5 by pressing on *WIRING* key within *Input* group.
4. The values to be measured (*current, voltage, power* and *energy*) were selected for each channel from 1 – 5 by pressing on *MEASURE* key within *Display* key group.
5. Establishing Ethernet local network between PM6000 and computer was done in *INTERFACE* menu within *System* group.

6. *DATA LOG* key is used to select the required channels to be logged.
7. After completing the wiring, data logging was done by pressing on *DATA DUMP* key

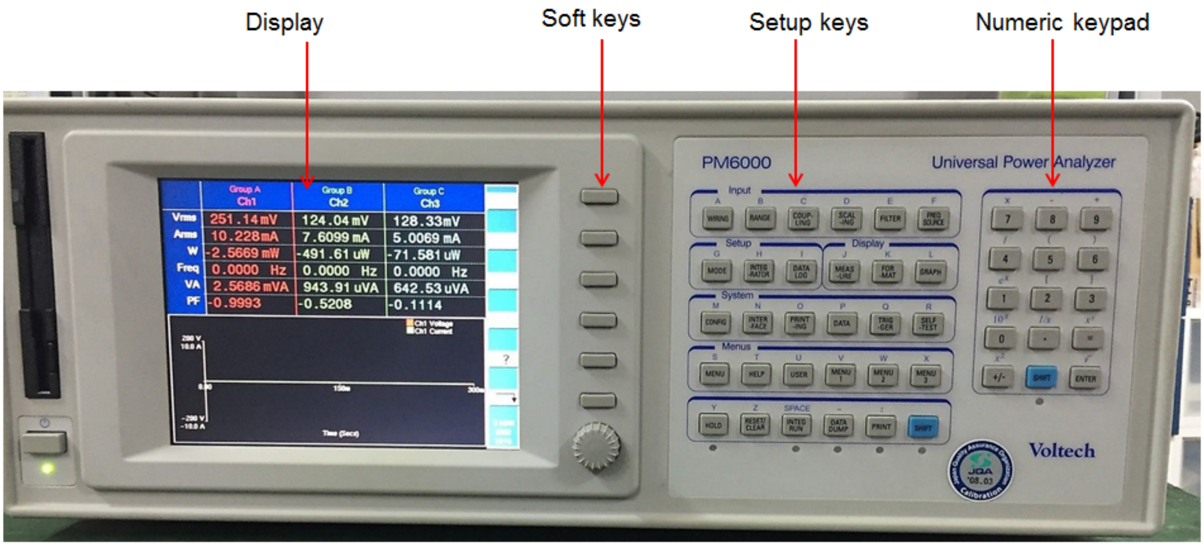


Figure A.3: Voltech PM6000 front view

- Voltech PM6000 Wiring

Wiring between PM6000 measurement channels and motor controllers is identical and needs to be done as shown in figure A.4 below.

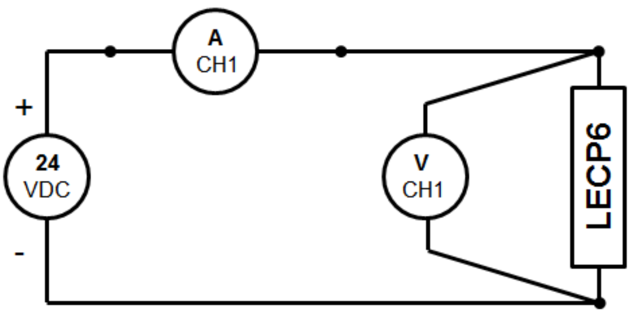


Figure A.4: Voltage and current wiring required on Voltech PM6000 channel per motor controller

Following are the steps of wiring device channels to actuators' controllers:

1. Station 4 was completely switched off by disconnecting its main circuit breaker.
2. Connected one yellow lead to yellow positive voltage input and one black lead to black positive current input on voltage input of PM6000 channel, same connections were made to current inputs. Yellow and black Dolphin clips were inserted to the loose ends of the current leads and the black voltage lead
3. In the station panel, unwired 24 V_{DC} that feed the controllers.

4. Connected new labelled wires instead of the unwired ones. Hence new connections could be made.
5. Wire external wire to $0V_{DC}$ terminal.
6. Using dolphin clips, yellow current leads and yellow volt leads per channel were shorted and then connected to new wires per controller that replaced the unwired 24 V_{DC} wires, black current leads were connected to the unwired $24V_{DC}$ wires, and black voltage leads were shorted together and connected to the external wire of $0V_{DC}$.

Figure A.5: Voltech PM6000 connection channels

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