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Mechatronic Simulation for Energy-Efficient Systems

Paryanto

Fertigungstechnik - Erlangen

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Mechatronic Simulation Approach for the Process Planning of Energy-Efficient Handling Systems

Mechatronische Simulation als Lösungsansatz zur
Prozessplanung von energieeffizienten Handhabungssystemen

Der Technischen Fakultät
der Friedrich-Alexander-Universität Erlangen-Nürnberg
zur
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Vorwort

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1. Introduction

Energy efficiency, process flexibility, development time and cost constraints are the main challenges in the development of handling systems (HS). Many researchers around the world from both industry and university focus on these challenges in order to develop HS that can be used efficiently and effectively.

The first challenge is the energy efficiency of mechatronic industries, a factor that is increasingly important due to stricter political guidelines concerning CO_2 emissions and the rising energy costs [1] [2]. For instance, based on "Energy Concept 2050", Germany should reduce greenhouse gas emissions by 40% by 2020, by 55% by 2030, and at least by 80% by 2050 [3].

The second challenge is process flexibility. Continuous increase of product variants is the main factor that leads to this challenge. Thus, HS should be flexible in their processes to handle high product variety. The handling and assembly processes must react quickly to adapt to an unplanned production process and ensure both economical and technical feasibility of flexible processes [4].

The third challenge is that the product life cycle of mechatronic products becomes shorter, which is caused by global competition among industry as well as customer trends. This means that mechatronic industries must update their products frequently [5]. Subsequently, the process planning schedule of HS must be performed within a short period of time.

The next challenge in the mechatronic industry is cost constraints. To reduce costs, the mechatronic industry must run efficiently and effectively in their HS' planning stages. This is because the planning stage has the greatest potential to reduce development and operational costs [6].

In short, all of these challenges can only be solved by implementing an efficient and effective planning approach, which needs detailed knowledge of the system behaviors (e.g. energy, kinematics and dynamics behavior) of handling machines, such as industrial robots (IR). Due to this fact, a mechatronic simulation approach is proposed to solve these issues, i.e. to analyze the system behavior of handling machines to support the process planning of HS.

1.1 Research background and motivations

The demand for high performance and low-energy consumption HS has grown dramatically in recent years. Therefore, planning engineers should be able to analyze the system behavior of HS machines using the best method to fulfill this demand. Since HS are complex systems, which consist of multi-domain engineering fields, the analysis of their behavior is a difficult task fraught with many obstacles [7]. Several methods have been suggested to develop high performance and low-energy consumption HS. However, most of these studies use knowledge-based development and experimental or analytical investigations. Knowledge-based development is very dependent on the engineers' skills, and is consequently unsuitable for long-term development. Several simulation approaches, which were developed using knowledge-based methods, are still difficult to implement in practical ways since it takes a lot of time and the knowledge transfer aspect is occasionally neglected [8]. Likewise, an experimental study on the physical HS prototypes is expensive, time-consuming and in most engineering cases, it cannot be realized. Moreover, analytical investigations of the system behavior of HS machines require a lot of effort and the results are mostly inaccurate. This is because under real conditions, there are many influences on the systems' performance, such as friction, heat, vibration and electromechanical losses, which are simplified or neglected in analytical investigations.

Additionally, the operating conditions of handling machines that consist of mechanics, electronics and informatics systems are difficult to be optimized and their energy consumption is difficult to be predicted. Thus, optimizations of these machines are very complex tasks. Therefore, a convenient method that can be used easily to analyze the system behavior and energy consumption is needed, which provide a higher accuracy at the early stage of the process planning phase.

The model-based approach, a method based on a computer model, is a common solution for analyzing system behaviors of HS machines since it is more compliant with time and budget constraints. However, model-based approaches for analyzing the mechatronic systems that are widely used for process planning and optimizing machines are not well integrated and the energy consumption analysis is not yet involved. Therefore, in this research, a mechatronic simulation approach that is used to analyze the system behavior and energy consumption of HS machines is developed.

This dissertation provides a mechatronic behavior analysis of HS machines, i.e. IR, in order to examine and optimize the HS performance. The mechatronic behavior analysis includes kinematics, dynamics and energy consumption analyses of IR (see Fig. 1).

The focus of the investigation is on IR since in actual conditions, almost all automated HS use IR as the main machine, such as in the automotive industry and in electronics production. Based on [9], the energy consumption of IR is approximately 8% of the total electrical energy consumed in general manufacturing processes. In the German automotive industry, IR consume up to 50% of the total energy in body shop processes. Therefore, a reduction of the energy consumption of IR is important in order to improve the productivity and efficiency of the HS [2]. Furthermore, the optimization of energy consumption of IR is not yet fully explored. Thus, there is still a significant potential in the improvement of the energy efficiency of IR, especially at the process planning stage.

The proposed approach uses multi-domain simulation tools based on the Modelica® modeling language. Modelica® is an object-oriented modeling language, thus making it suitable for planning engineers, which come from different areas of expertise. It allows multi-domain engineering fields in a simulation model and is able to analyze the system performance, e.g. its energy consumption and the system behavior in a single simulation environment. Furthermore, this research is concerned with the optimization of operating parameters (e.g. speed and payload) of IR. This is due to the fact that operating parameters of IR are strongly related to their energy consumption [10]. For a validation of the modeling concept and simulation model, the results from the simulation will be compared with values acquired experimentally.

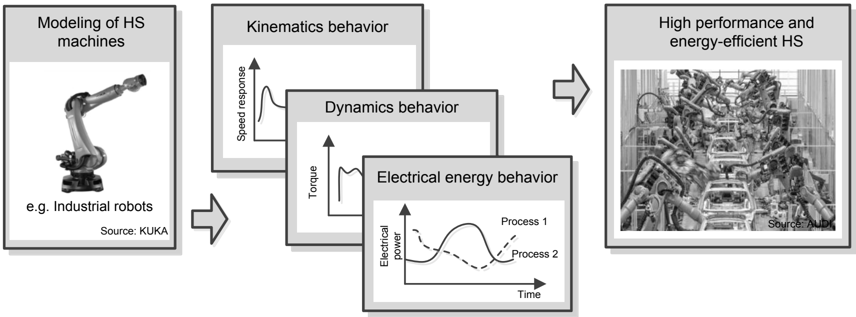

Figure 1: A mechatronic simulation approach as the basis for process planning and optimization of handling processes

1.2 Objectives of the research

The aims of this research are to develop a modular mechatronic simulation model of HS machines, i.e. IR that can be used in the process planning of HS by involving a multi-domain simulation paradigm. In other words, it can be used to analyze the energy consumption behavior of the machine as well as its kinematics and dynamics behavior. Thus, by means of the simulation results data, the planning engineer can define the most effective and energy-efficient conditions of the robot. The method deals with the integration of a simulation tool based on Modelica® language and computer aided design (CAD) data.

The following specific objectives have been defined to support the main goal of the research:

- develop modular models of the HS machine, i.e. an IR, that can be used to predict and analyze the kinematics and dynamics behavior as well as the energy consumption of the system,
- evaluate and validate the developed simulation model,
- analyze the energy consumption, kinematics and dynamics behavior of an IR,
- define strategies to reduce the energy consumption of IR by optimizing its operating conditions using the developed simulation model.

The application of the developed approach is demonstrated on a HS that is a part of an electronics production line, called the universal contacting module (UCM) cell.

1.3 The outline of the dissertation

A brief problem statement and the objectives of this dissertation have been outlined in this chapter. The next chapter starts with a discussion on challenges in the planning and optimization of energy-efficient HS. Chapter 2 also gives a literature review and an extensive explanation of related work in the planning and optimization of HS. At the end of Chapter 2, the deficiencies of current solutions/methods for process planning of energy-efficient handling machines are presented and the selected approach to cope with these drawbacks is proposed.

Chapter 3 describes the fundamentals of mechatronic simulation methods as the basis for process planning and optimization of HS. This chapter gives a concise discussion about object-oriented modeling, multi-domain simulation paradigms and the integration concept of mechatronic simulation into process planning of handling machines. Chapter 4 provides a modeling procedure of the handling machine, i.e. an IR. In this chapter, the modeling methods of IR components using multi-domain simulation tools based on Modelica® are presented in detail. Chapter 5 presents the verification and validation method used for the digital model of the IR. For the purpose of validation, the simulation results will be compared with the results from an experimental investigation. The analysis and discussion concerning the model accuracy and its limitations is also provided in this chapter.

Chapter 6 presents the analyses of the kinematics and dynamics behavior of an IR, which is acquired from the simulation and experimental results. Chapter 7 presents the energy consumption analysis of IR. The analysis of the effect of the operating parameters and dynamics behavior of IR on the energy consumption are provided in this chapter. Afterwards, the optimizing of IR as a component of HS is presented in Chapter 8. In this chapter, the discussion is focused on a strategy to reduce the energy consumption in relation to the robot productivity as part of the HS. The main conclusions of the system behavior analysis of HS using the mechatronic simulation approach are presented in Chapter 9. Further work and suggestions for future research concerning the process planning and system behavior analysis of IR are also provided in this chapter.

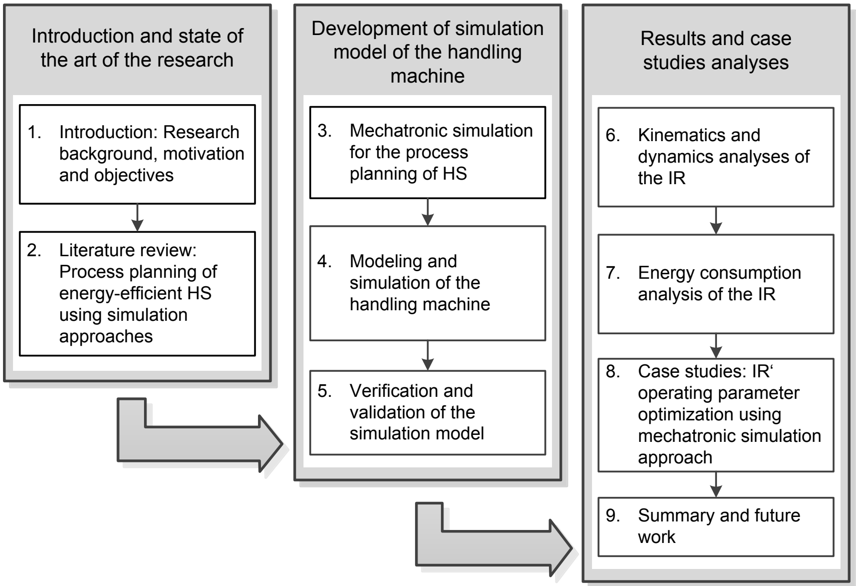

Figure 2: Outline and structure of the dissertation

A summary of the content of the dissertation and the relation between the chapters is shown in Fig. 2.

2. State of the Art in the Process Planning of Energy-Efficient Handling Systems

Manufacturing process planning describes the detailed work and system that is required for the fabrication of a product based on its design specifications and the availability of manufacturing resources [11]. It includes activities such as the selecting and sequencing of manufacturing processes, the defining and optimizing of machine operating parameters, and the calculating of handling time and costs. Since the process planning and optimization of HS always involves engineers from several areas of expertise, including mechanics, electrical engineering and informatics, practical tools are required to act as an interface for interdisciplinary planning of the systems and optimization of their process parameters. These tasks are further complicated by the different paradigms of engineering experts from diverse educational backgrounds. Indeed, there are many challenges in the planning and optimization of HS that remain.

Many solutions have been developed by engineers and by scientists to solve these issues. Therefore, the first step of this research addresses the literature review of process planning and optimization processes for HS with focus on the energy efficiency issue. This chapter begins with a discussion of challenges in the planning of HS that are used in mechatronic industries. Next, discussion on the system behavior analysis for the planning and optimization of HS is presented. In the next sub-chapter, existing methods that are available in the literature are described in more detail.

Furthermore, simulation methods that have been proposed by scientists and engineers to analyze the system behaviors of machines are presented. Then, a brief outline in technology related to the process planning and optimization of HS and the discussion of existing simulation methods are provided. In addition, a review of the existing methods for reducing the energy consumption of IR is described. Finally, a solution approach to solve existing problems in the context of process planning and optimization is described at the end of this chapter.

2.1 Challenges in process planning of handling systems

There are many challenges in the planning and optimization of HS, which are the result of several issues in production, which are the rapid shortening of the product life cycle, the continuous increase of product variants, miniaturization and cost constraints. These challenges lead to the development and optimization of HS which are more complex. For instance, short life cycles mean that the process planning phase of HS should likewise be reduced and improved [12]. The continuous increase of product variants also pushes the mechatronics industry to shorten the development cycles of HS. Unlike mass production systems (PS) that produce only a few variants of a product, the mechatronics industry is required to attend to many product variants that are only produced for shorter periods [13]. This requires an effective planning approach.

The miniaturization trend of mechatronic products also pushes the industry to produce high precision and high accuracy HS. This means that a planning engineer requires a best practices approach for planning and optimizing HS. Moreover, a significant reduction of the handling cost can only be achieved by implementing an efficient approach to process planning since about 70-80% of the energy costs are defined during this stage [6]. Planning and commissioning processes account for about 50% of the total costs of PS development [14]. These factors will play an increasingly significant role in the future with the additional complexity of mechatronics products through the development of new technologies. Thus, an approach, which can be used to reduce the time taken for the process planning and optimization process of HS, is desired. Research on improving planning can help manufacturers to reduce energy and development costs, speed up development processes and improve the process flexibility of HS.

Besides the aforementioned factors, the energy consumption of HS becomes more important due to the increase of energy prices, a stricter energy policy and an increase of environmental awareness [15]. Therefore, in HS' development, process planning with focus on the reduction of energy consumption receives increasing attention from the planning engineer.

To summarize, in the planning process of HS, the following challenges should be addressed:

- energy efficiency of HS,
- development time and operating cost of HS,
- process flexibility and complexity of HS,
- quality and reliability of HS.

The detailed descriptions of these challenges are presented in the following sub-sections.

2.1.1 Energy efficiency

Energy efficiency has become the main issue in the development and optimization of HS. Energy prices, policy guidelines concerning CO_2 emissions, corporate identity and flexibility in the energy supply are among the factors that lead the industry to reduce energy consumption in their manufacturing process. According to [15], these factors are generally classified into push and pull factors (see Fig. 3). Push factors come from government policy (e.g. restricted emissions as a result of global warming) and from technology such as the development of efficient electric drive systems. On the other hand, pull factors come from the company's vision such as company targets and from market demand. In addition, incentives from the government and research funding opportunities also pull the industry to reduce energy consumption in their manufacturing plants.

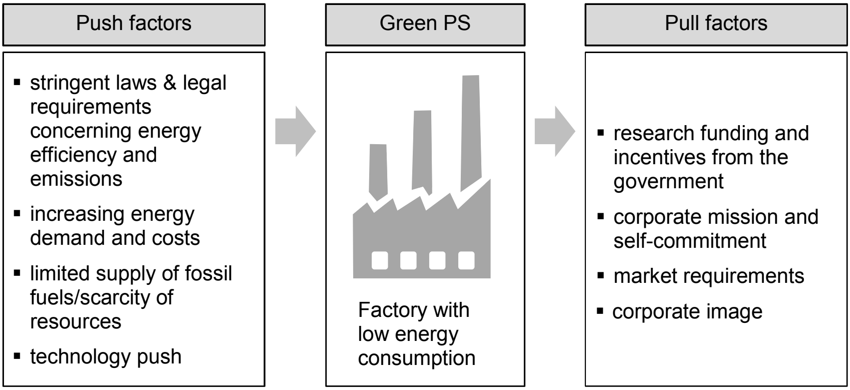

Figure 3: Drivers for sustainability for manufacturing companies (based on [15] [16])

Furthermore, energy prices for industry particularly in Germany continue to increase, which is caused by the planned nuclear phase-out that has been agreed upon and by the dwindling of oil reserves [17]. Thus, the manufacturing industry strives to reduce their energy consumption in order to keep their products competitive as well as to improve their corporate image. Based on [18] [19], German manufacturing industries are responsible for about 47% of the total national energy consumption (see Fig. 4). This makes the energy efficiency in manufacturing systems not only a single company issue but also a national or even global challenge. Therefore, the CO_2 emissions reduction target of at least 40% in 2022 for Germany is impossible to reach without involving the industry sector.

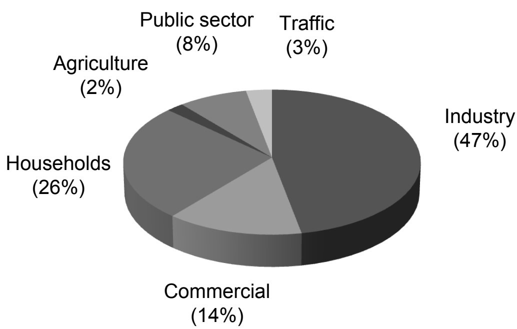

Figure 4: National energy share in Germany [18] [19]

In order to solve these challenges, since 2010 the German government offers many research programs and incentives to reduce energy consumption in manufacturing plants. For instance, research projects that have been launched for reducing the energy consumption of manufacturing processes include *eniPROD* [20], *InnoCaT* [21], *EnEffAH* [22] and *SimEnergy* [23]. While in Bavaria similar projects are *FOREnergy* [24] and *Green Factory Bavaria* [25].

The energy efficiency project called *eniPROD* (energy-efficient production processes) started in 2009 and is coordinated by the Technical University of Chemnitz and the Fraunhofer[1] Institute for Machine Tools and Forming Technology (IWU) in Chemnitz. The *eniPROD* project's aim is to improve efficiency of PS through increasing resource efficiency of production processes [20]. Furthermore, energy efficiency projects that are also related to the manufacturing processes in the automotive industry are *InnoCaT* and *SimEnergy*. Both of these projects use discrete event simulation (DES) approaches in order to predict and optimize the energy usage in manufacturing processes.

Another project is called *EnEffaH* (Energy Efficiency in Production in the Drive and Handling Technology Field), which has the goal of developing methods, tools and products for an energy-efficient automation. This project is conducted by the Institute for System Dynamics, University of Stuttgart in cooperation with the Fraunhofer Institute for Systems and Innovation Research (ISI) and several automation companies, including Festo AG and Metromix [22].

Further, to cope with the flexibility of energy sources, the Bavarian Research Foundation provides grants for the project *FOREnergy* that is aimed at defining concepts and solutions for energy flexibility in production. This project started in 2012 and is conducted by several research institutes and partners from industry within the Free State of Bavaria. Besides the *FOREnergy* project, the Free State of Bavaria also grants a collaborative project called *Green Factory Bavaria*. This project involves several universities in Bavaria (e.g. University of Erlangen-Nuremberg, Technical University Munich, University of Applied Sciences Nuremberg, Fraunhofer Institute and industry partners, such as Siemens AG and Audi AG). The core objective of the project is the transfer of knowledge from applied research to the industry to increase energy and resource efficiency of manufacturing processes. To achieve this objective the so-called "Green Factories" in Bavaria are constructed as a demonstration, learning and research platform. Both technical solutions and methodology are developed to reduce energy consumption in production processes [25].

[1] Fraunhofer is one of the largest German research organizations that focuses on many fields of applied science and engineering. It is named after Joseph von Fraunhofer who was an engineer, a scientist and an entrepreneur.

In addition, there are several projects in the European Union (EU) under the *Seventh Framework Programme* (FP7) that focuses on the energy efficiency of manufacturing industries. Among those projects are:

- ENEPLAN: Energy Efficient Process Planning System [26]
- CASES: Customized Advisory Sustainable Manufacturing Services [27]
- AmI-MoSES: Ambient-intelligent Interactive Monitoring System for Energy Use Optimisation in Manufacturing SMEs [28]
- DEMI: Product and Process Design for AmI Supported Energy Efficient Manufacturing Installations [29]
- ESTOMAD: Energy Software Tools for Sustainable Machine Design [30]
- AREUS: Automation and Robotics for European Sustainable Manufacturing [31]
- EMVeM: Energy Efficiency Management for Vehicles and Machines [32]

Although these projects have been undertaken, prevailing process planning approaches that prioritize the optimization of the energy consumption of HS are based on expert systems, which can provide several alternative process plans [33]. While this is useful to analyze the handling process in general, it has limited use for optimizing the specific handling machines in greater detail.

To improve efficiency, the energy consumption of HS should be able to be defined and optimized at an early stage of development, especially in the process planning stage [34]. This is because the planning phase that is used to develop and optimize handling operations has significant impact on the energy consumption of handling processes.

2.1.2 Development time and operating costs

“Faster, better and cheaper” is conventional wisdom among professionals working diligently to complete development projects [35]. This term also applies to the process planning and optimization of HS since manufacturers need to reduce HS’ development time in order to reduce time-to-market and development costs. Due to this reason, process planning of HS should be performed in a short time period and in line with the productivity requirements. Thus, system behaviors of every handling machine must be easy to analyze in order to reduce the amount commissioning processes required. For this reason, a modeling and simulation approach becomes a powerful method since it enables the integration of multi-physical domains [7]. Therefore, a better integration process can be achieved between design and commissioning processes.

According to [36], the main objective of research into manufacturing planning is to reduce manufacturing costs by optimizing manufacturing sequence planning and manufacturing line balancing. In that context, the optimization of operating parameters of handling machines is the key factor since it is needed in both of these phases. The operating cost of HS will not only influence the product prices but also the profit of a company. In addition to the reduction of the energy consumption of HS that was pointed out in the previous sub-section, reduction methods of operating costs can be performed for example by optimizing the operating parameter of the handling machines and sequence time. Thus, an effective and efficient method for process planning and optimization of HS machines is desired.

2.1.3 Flexibility and complexity

Due to the fact that products should at all times be tailored to match specified customer requests, the HS must be flexible enough in its processes in order to be used for the production of a greater number of product variants. In short, HS should have the ability to produce several product variants [37]. This requirement drives the manufacturing industry to search for an effective and efficient method for the development of flexible HS [13]. However, not all product variants can be accounted for in the initial development stage or during the planning of the HS. Thus, it is usual that the system engineer is not able to validate the plant with regards to all product variants [38].

Although product variety can be achieved at different stages of product realization, e.g. during design, fabrication, manufacturing or sales, developing product variety during the handling process is the most cost efficient method [39]. This is because variations of the final product can be achieved using handling or assembly process combinations, e.g. with a product family architecture (PFA) approach [40]. The common standard solution to deal with the flexibility of the manufacturing process is by using a flexible manufacturing systems (FMS) concept. However, the FMS is very challenging to implement [37]. Despite this, several researchers have advanced possible solutions for FMS. For instance, Koren, *et al.* [41] have given a general explanation concerning reconfigurable manufacturing systems (RMS). Using the RMS approach, the HS is able to assemble several product variants.

Moreover, the rapid advancement in the informatics field pushes manufacturing industries to integrate the latest electronics technology in their systems. This integration is used to improve performance and flexibility of products. Customers generally want a new product that is not only durable but also embedded with the latest information technology. For example, the mechatronic system must cope with the advancements of Industry 4.0, such as cloud data storage, real-time connection with the internet and can be instructed by a human voice. All these requirements are very challenging from a manufacturer's point of view, especially for the manufacturing process planning.

2.1.4 Quality and reliability

Industries in constant competition with one another strive to bring products to the market that have a superior cost-performance ratio versus their competitors. For this reason, it is in their interest to focus on the development process of HS, since they have a significant impact on quality and thus customer satisfaction [42].

According to Tatikonda [35], the quality of the product is not only measured by the final product performance, but it also involves the development process measurement. Thus, product quality usually can be seen from its lifetime, features, energy efficiency and reliability. Product's users often define those criteria, while quality in the development process refers to the performance of systems and organizational processes, as well as strategic planning processes. Typically, system engineers and management personnel, such as design managers define the quality of the development process.

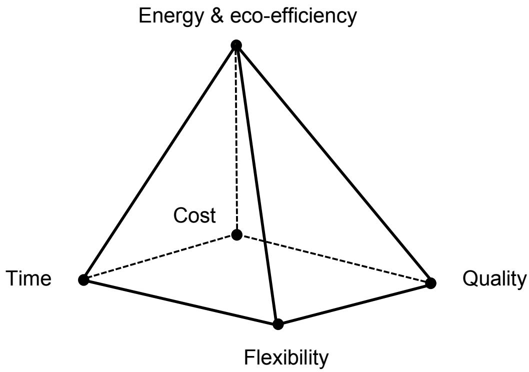

Figure 5: New manufacturing decision-making attributes with the inclusion of energy and eco-efficiency [43]

The high quality standard of HS is defined by the few number of defects detected in the development stage and the low number of design changes to the specifications. In addition, based on the manufacturing approach, a high-quality product means that the product performance meets the defined requirements in line with the manufacturing design. Based on these requirements, it can be concluded that a new process planning of HS should not only be focused on the old manufacturing tetrahedron paradigm (i.e. time, cost and quality) but must also involve flexibility and energy & eco-efficiency in its attributes, as shown in Fig. 5.

2.2 Simulation approaches for the process planning of handling systems

Planning engineers commonly use simulation approaches for engineering analysis, including for process planning and optimization of HS. In the process planning phase, they use simulation approaches for optimizing and improving performance of handling processes. Essentially, simulation approaches have the following advantages:

- ability to predict the system behavior of the handling process and its components without waiting for the physical prototype or real system to exist [44]. Thus, it can reduce development time and costs since it is not necessary to build an expensive prototype.
- ability to predict and understand the impact of a design across different engineering disciplines in the early step of the development [45]. Thus, it is very useful to improve efficiency and productivity of the processes.
- ability to provide a virtual platform for offline training of operators and for evaluating the processes and the sequences in the early planning phase [46].

However, the simulation approach as a new trend in the planning and optimization of HS also comes with several disadvantages, such as a lack of integrated simulation platforms that can be used in all development stages [7]. Furthermore, some of the available software tools are expensive. Moreover, due to the diversity of simulation tools that are available on the market, the selection process for choosing suitable software for specific handling processes is increasingly difficult [47]. The classification and identification of available simulation software is needed in order to choose the best solution for planning and optimizing HS.

In this section, several planning methods, which use simulation approaches, are discussed. Firstly, the current standard approaches, which are commonly used by engineers for the planning and optimization of HS, are presented. After that, the types of simulation approaches for analyzing HS at the planning stage are explained. Furthermore, the common simulation approach that is used for predicting kinematics and dynamics behavior of HS is provided. Finally, energy simulations of HS are described at the end of this section.

2.2.1 General methodology

A methodology that is generally used for the planning of HS in the industry is based on the VDI[2] guideline 2221 [48], which is developed to design technical systems and products. This guideline defines the general step for system planning, including planning of HS. The VDI 2221 methodology breaks down the general task into defined sub-problems. Thus, solutions can be found and implemented more easily. The general methodology of VDI 2221 is shown in Fig. 6, which consists of the problem analysis, problem definition, system synthesis, system analysis and evaluation and ending at decision-making.

[2] VDI stands for Verein Deutscher Ingenieure (Association of German Engineers)

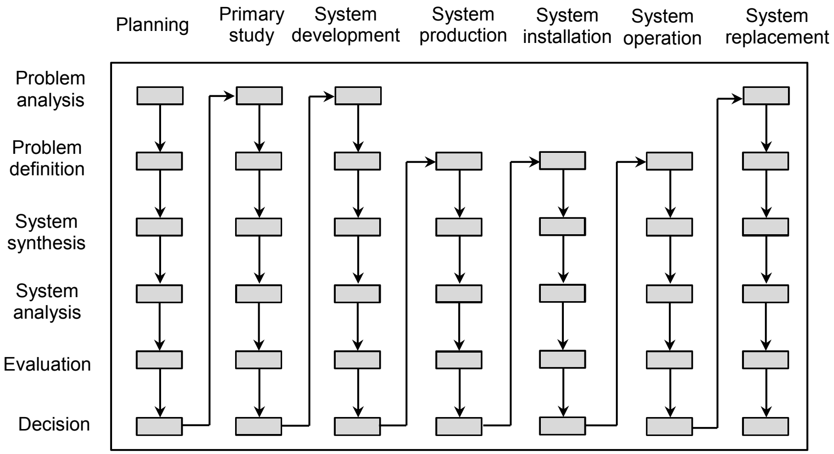

Figure 6: Systematic approach for developing technical systems [48]

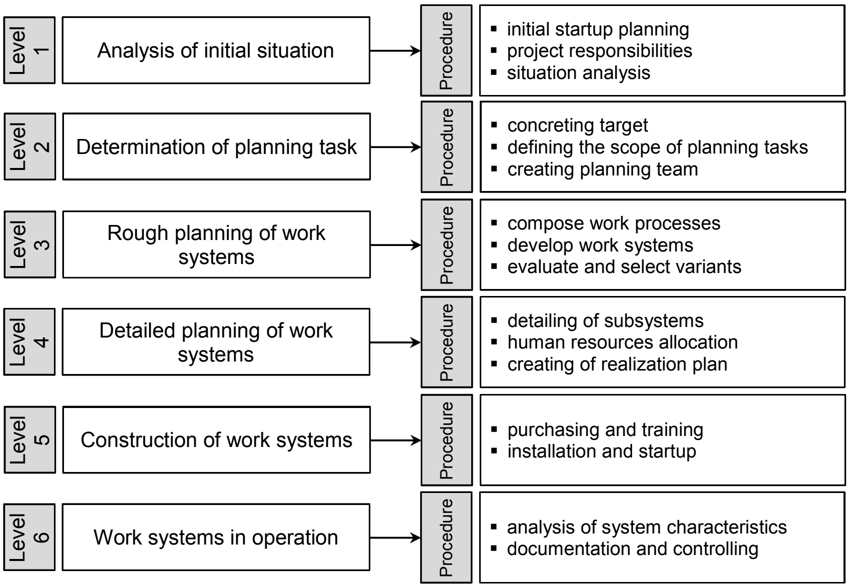

Figure 7: Planning method according to REFA [37]

Another general planning methodology was developed by REFA (*Reichsausschuß für Arbeitszeitermittlung*), a non-profit organization for work-study, industrial organization and corporate development. The REFA planning methodology is shown in Fig. 7. The methodology is focused on the work design in order to improve organizational works and process management. The methodology comprises of six levels, with every level consisting of specific procedures (work design) that should be accomplished before the planning engineer proceeds to the next level. To improve the process management, suitable tools and methods support each of the planning levels [37]. Although the REFA method was not specifically designed for HS development, the method is reliable for the planning of PS.

According to Marian [49], the development of HS is divided into three main phases, i.e. product conception and design, production planning and manufacturing processes (see Fig. 8). All of these phases have different issues in order to realize effective and efficient HS. In the product conception and design stage, the issue is to design for the assembly and disassembly process, with a focus on the design of the product itself.

In the production planning stages, the issue is to define the handling planning with a focus on the sequence processes. Further to the manufacturing process stages, the assembly issue is to define its operations with a focus on the optimization of automation and its operations. In this dissertation, the focus is on the production planning and manufacturing processes. Within these stages, the task is to define and optimize the operating parameters of the handling machines.

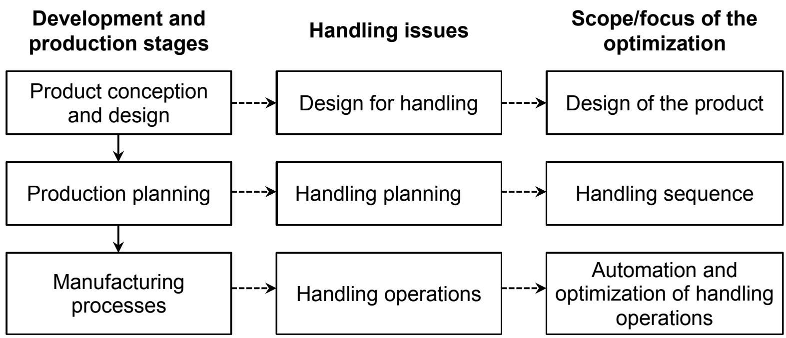

Figure 8: Development stages of handling or assembly systems (based on [49])

Another planning methodology is the RFLP approach, which stands for *Requirements, Functional, Logical and Physical* that represent the stages of the development process. This approach is based on the systems engineering paradigm that integrates all engineering activity for the development of complex technical systems, ranging from requirement analyses to testing and validating of technical systems [50]. As shown in Fig. 9, the RFLP approach is focused on the integration and optimization of the V-model using full-integrated system analysis.

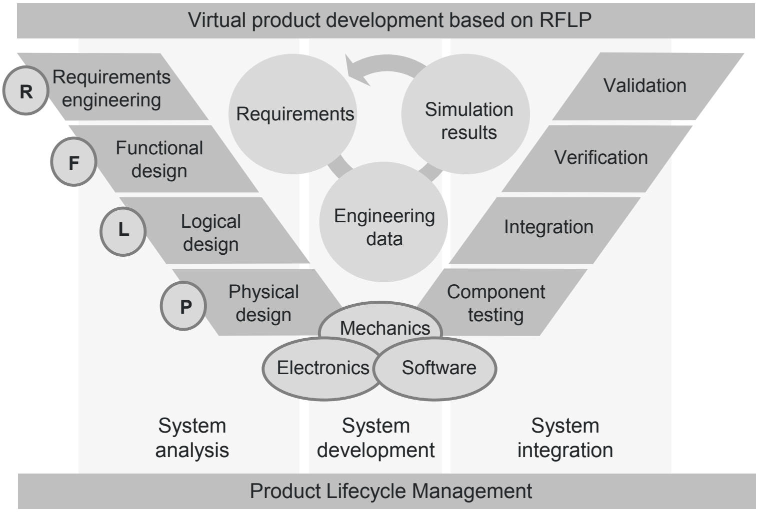

Figure 9: Virtual systems development based on systems engineering and RFLP [50]

The RFLP approach describes every stage of system analysis of a HS using integrated computer aided engineering (CAE) tools. The product requirement, function, logical behavior as well as physical design can be linked directly to each other and thus the development time can be dramatically reduced.

Based on the present methods, the planning of HS, which are categorized as complex technical systems, can be performed. However, due to the current challenges in the planning of HS as mentioned in Section 2.1, an integrated simulation approach for the planning process is required. Therefore, it is important to involve a mechatronic simulation approach in the current planning methodology. In the next sub-section, conventional simulation approaches that are used in the planning of HS will be described.

2.2.2 Types of simulation

Several simulation types for the planning and optimization of HS are available on the market. According to [47], the application area of simulation tools in the manufacturing industry is very wide. Simulation methods have applications from conceptual product design to facility systems analysis (see Tab. 1). Therefore, an understanding of the functionality of these simulation tools is mandatory in order to choose the right one. For instance, the DES approach is usually used for analyzing the material flow and logistic operations in a HS. A software tool such as *Plant Simulation* from Siemens is one of the simulation tools that are commonly used for this purpose. The software allows planning engineers to execute experiments on the computer model before the real system exists.

Table 1: Simulation types used for manufacturing processes (based on [47])

Simulation name (type)	Application
Conceptual product design	2D sketching, dimensioning and 3D modeling of the conceptual design
Detail product design	3D modeling and structuring of the design
Tolerance simulation	Tolerance fit analysis between the components for assembly and manufacturing purposes
Mechanical simulation	Dynamics and structural analysis of sub-assemblies
Digital mock-up	3D visualization of full product assembly
Ergonomic product simulation	Insertion of human models for ergonomic analysis
Machine process simulation	Planning of machining operations, collision detection in the workcell and programming of NC machines
Machine tool path simulation	Detailed operational planning of the tool piece and programming of NC machines
Robotic cell simulation	Planning of robot operations for the manufacturing task
Assembly sequence simulation	Planning and analyzing of the assembly sequence
Human task simulation	Human movement modeling, task analysis and workstation assessment for manufacturing activities
Facility layout simulation	Spatial analysis of the factory layout
Facility system simulation	Analyzing manufacturing process flow, calculating the overall throughput and identification of resources required

Besides material flow simulation, mechanical simulation is also commonly used to analyze a single machine, which is a part of a HS. Mechanical simulation includes dynamics simulation tools, finite element analysis (FEA) and computational fluid dynamic (CFD) simulation. Dynamics simulation is used for analyzing the system behavior of the machine including kinematics and control behavior. On the other hand, FEA and CFD are very powerful for analyzing structural issues of the machine (i.e. solving for deformation and stresses in solid bodies or dynamics of structures) and for analyzing the conditions surrounding the machine (i.e. solving for temperature distribution near the machine) [51] [52].

A further simulation type is tolerance simulation. This kind of simulation is used for checking and analyzing the tolerances and fits between two or more assembly parts. This simulation method is integrated in some CAD software tools. Complementary to the mechanical simulation and tolerance simulation, a digital mock-up simulation is also commonly used to analyze handling machines. This simulation method is able to visualize the full product assembly in 3D with all internal complexities, which include internal fits and interface analyses of the final assembly [47].

In the context of process planning, simulation types that deal with the correlation between several machines are commonly used. These are, for example, machine process simulation, machine tool path simulation, robot cell simulation, assembly sequence simulation and human task simulation.

As shown in Tab. 1, the machine process simulation and machine tool path simulation are used for planning machining operations, for collision detection among the machines in the workcell and for planning the numerical control (NC) machine operations. Meanwhile, the robot cell simulation and assembly sequence simulation find practical use for the planning of robot operations, e.g. for welding, machining and painting tasks, for assembly operations, and for analyzing the sequence of assembly tasks as well as disassembly and reassembly operations.

At the factory level, the simulation tools that are commonly used are facility layout simulation and factory system simulation. Facility layout simulation is suitable for spatial analysis and is applied to assess machines in the manufacturing facility. Related to this, planning engineers use facility system simulation to simulate the manufacturing flow as well as calculate the throughput and the resources required for the intended manufacturing processes.

In the development of HS, these simulation methods complement each other. Therefore, integration among the simulation methods is needed. The general correlation between these simulation methods is shown in Fig. 10. Based on this figure, it becomes clear that the machine process simulation has a big impact on other manufacturing stages, i.e. product design and facility design. Thus improving the advantages from machine process simulation will result in a greater improvement of efficiency and effectiveness of the planning processes of HS.

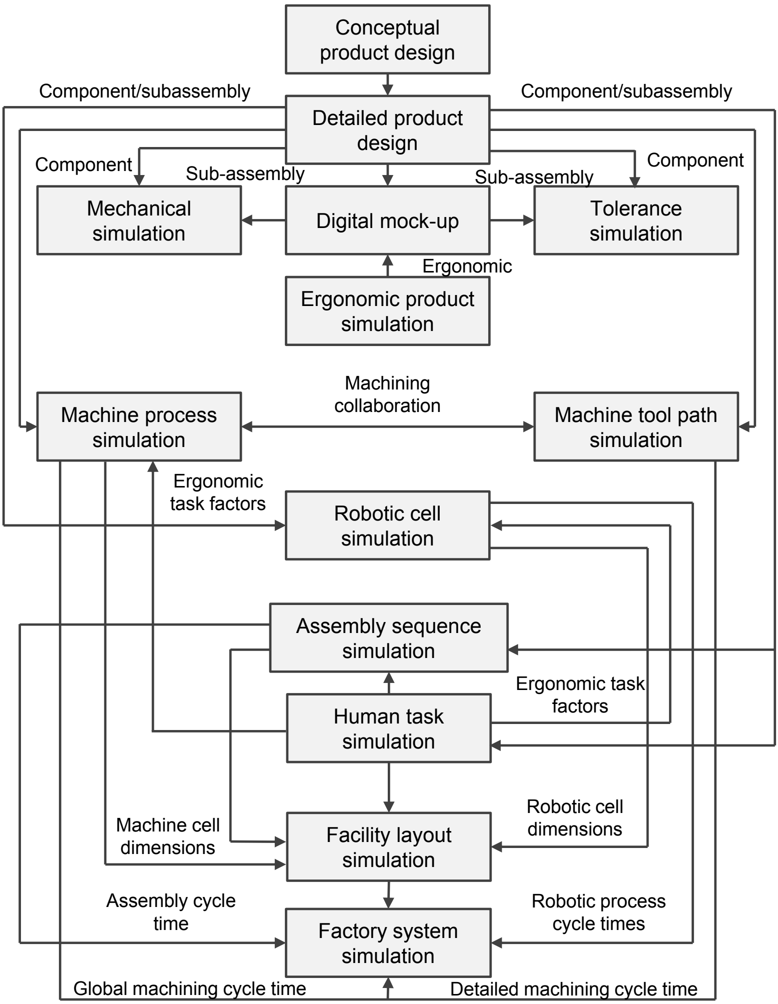

Figure 10: Simulation types in the planning of manufacturing systems (based on [47])

2.2.3 Energy consumption simulation of handling systems

Predicting and analyzing the energy consumption of HS is not taken into account in the conventional planning process. The requirements of low-energy consumption as well as low CO_2 emissions started in the early 21st century after the cost of energy for industry arose and after the Kyoto Protocol [53] entered into force in 2005. Because of this, industry, as the main source of CO_2 emissions (either directly or indirectly), must reduce energy consumption to suppress this amount. Due to these reasons, current PS are getting more complex; the initial manufacturing paradigm has shifted from mass production that started in 1913, to sustainable manufacturing in the 2010s, as shown in Fig. 11.

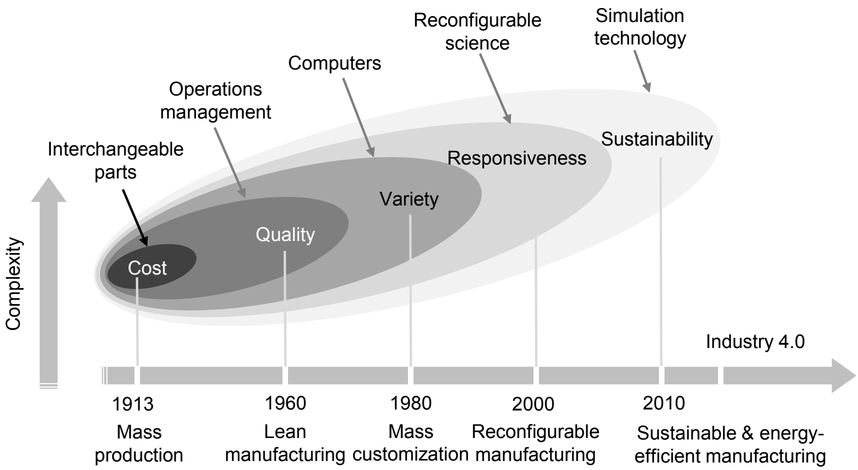

Figure 11: Evolution of complexity of PS (based on [54] [55])

Fig. 11 shows that the objective of mass production is to reduce cost by producing interchangeable parts. Lean manufacturing introduces the new objective to increase product quality by implementing integrated operations management. Further, the new manufacturing paradigm of flexible manufacturing aims to increase part variety by using computer technology. After that, in the year 2000 the production paradigm shifts to reconfigurable manufacturing, which has the objective of making manufacturing process more responsive to cope with the market requirement that requires more variety in products [55]. The latest paradigm shift is to sustainable manufacturing, which means that the manufacturing system aims to improve its efficiency in energy usage for reducing the environmental impact as well as the operation costs. This requirement leads to the development of efficient HS with low-energy consumption.

Since the complexity to design a sustainable manufacturing system is very high, planning engineers use a simulation approach in order to support the planning process. In sustainable manufacturing, there are a multitude of variables and conditions that must be considered, in which case a simulation approach could be of great interest. [56]

The simulation approach for the development of energy-efficient HS commonly uses material flow/factory simulation based on DES. Typically used in a supporting role in the design phase for evaluating and optimizing the concept before investment decisions are made. DES tools such as material flow simulation provide a convenient method for identifying common production process waste that occurs in HS, such as waiting periods in logistics and manufacturing processes. However, this simulation cannot analyze the energy consumption of every machine that is used as a handling component. Optimization of these machines is only based on operation manuals that in most cases are not effective for analyzing all of the machine operations. The data from vendors is not precise, mostly indicating only the maximum energy consumption. In addition, the manuals only provide data about energy for certain operation processes.

According to [56], the focus of research for the development of energy-efficient HS is on the development of an integrated simulation method that has the ability to analyze and optimize the handling process as well as address the energy and environmental impact. Thus, DES tools are insufficient to analyze the whole process. Instead, incorporating mechatronic simulation to analyze the energy consumption of every handling machine, including IR, offers great advantages in regards to reducing the energy consumption of the system as a whole.

2.3 Related work

In this section, research based on the simulation approach which has been proposed by scientists and engineers are presented. Furthermore, more specifically, this chapter presents the literature review of the existing methods for reducing the energy consumption of IR used in a HS.

2.3.1 Research-based solutions

Research on manufacturing planning using a simulation approach started in the 1990s with the application of CAD for designing products. Since then, manufacturing planning using simulation approaches has shown the ability to reduce development time as well as improve manufacturing efficiency since potential problems can be identified without the use of physical prototypes [46]. For instance, Toyota Motor Company, by using simulation approaches for solving handling issues in their design phase, is able to reduce development costs by 50%, shorten lead-time by 33% and reduce design variations by 33% [57]. Meanwhile, Daimler AG is able to reduce their planning time for handling within the body shop area by 30% [57]. Further, Ford is able to reduce employee injury during assembling as well as improve the quality of new vehicles by implementing virtual manufacturing simulation for process and ergonomic analyses [58].

Due to these improvements, research on handling planning using simulation approaches carries on under various research groups. Several institutes are exploring the potential development of future HS planning technology, with the focus on the improvement of the HS's efficiency.

With regards to this, the main past and on-going research that focuses on the development of an efficient and low-energy consuming HS, including the simulation approaches, are presented as follows.

Fysikopoulos' approach

In 2014, Fysikopoulos [43] developed a general approach to design energy-efficient PS. Here, manufacturing systems are divided into four levels, namely the process, machine, production line and factory levels. An analysis is performed on every level to find the optimum energy consumption. Analysis on the process level is mainly performed to optimize the majority of manufacturing processes. For example in laser machining, the analysis focuses on the energy of laser beams. On the machine level, analysis aims to find the optimum for the various machine-process operating parameters, such as the speed of the machine tool operations. On the production line level, the analysis focuses on a group of machines including any other devices that are used in a production line. Factory-level analysis concentrates on the interaction among several production lines and other peripheral systems that exist in the factory. The illustration of these four levels is depicted in Fig. 12.

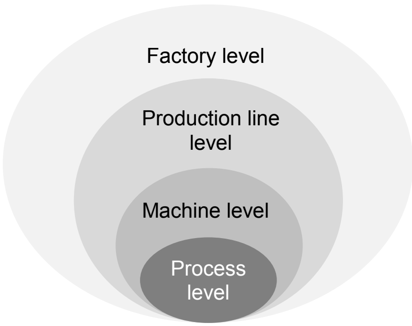

Figure 12: Energy efficiency analysis division [43]

Based on the analysis of these four levels, Fysikopoulos found that the machine level accounts for a significant portion of the energy consumed. Therefore, optimizing this level can reduce the energy consumption of HS significantly. For example, in laser drilling processes, optimizing the laser's operating parameters, e.g. pulsing frequency and beam focusing quality, can reduce the energy consumption of the handling process significantly. [59]

The proposed approach by Fysikopoulos divides the process analysis in several levels and appears promising for the use of designing a low-energy consumption HS. However, the approach does not go further into detail and simulation approaches, despite being the current trend in the process planning of HS, are not fully introduced.

Thiede and Hermann's approach

Thiede and Hermann [1] [18] [60] [61] from the Institute of Machine Tools and Production Technology (IWF), Braunschweig University of Technology propose an approach based on simulation technology to develop an energy-efficient manufacturing system. The simulation approach is used to evaluate the environmental aspects in manufacturing processes such as environmental temperature, gas emissions, material scraps and heat/waste energy.

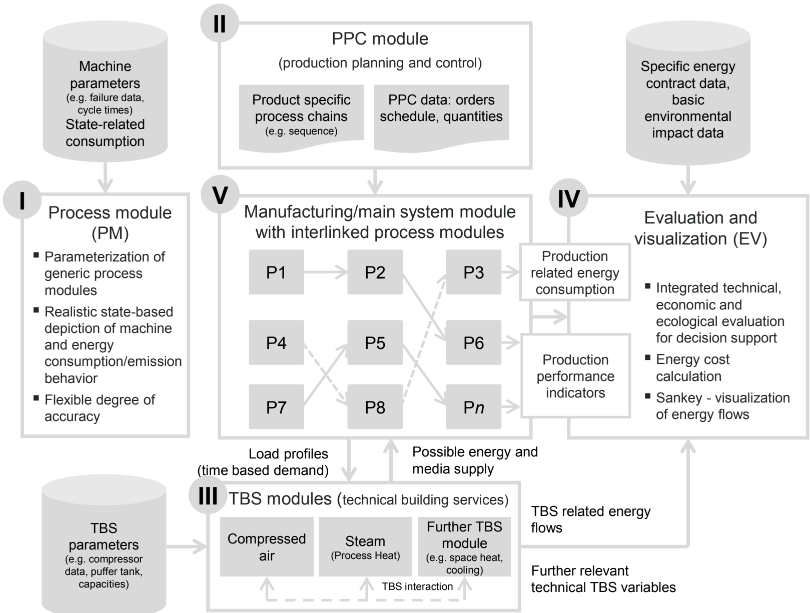

Figure 13: Framework of Thiede and Hermann's simulation approach [1]

The focus of their approach is to evaluate the energy flow and its impact on the environmental conditions. The basis of the evaluation is on the process chain of a manufacturing system. Rather than analyzing individual machines of HS, a simulated environment is developed that is flexible for several manufacturing industries. The simulation environment is used to evaluate the energy flow of all factory subsystems, including their dynamics. The concept of their approach is depicted in Fig. 13.

In their approach, the manufacturing processes are divided into several modules, of which every module provides information on its energy flow. Thus, the energy flow of each process as well as the whole system can be evaluated and visualized. Since the simulation approach is designed to deal with several industry processes, it can be used for several manufacturing industries such as in casting and machining.

Their usage of the simulated environment is based on a hybrid approach, which is a combination of continuous and DES. Thus, the approach can be used to evaluate not only energy data but also its environmental impacts. However, since the approach deals with the system as a whole, the energy analysis of individual manufacturing machines and their processes cannot be fully explored. Therefore, the approach's capability to improve the energy efficiency of HS is limited.

Weinert and Seliger's approach

Weinert and Seliger [62] [63] from the Institute for Machine Tools and Factory Management (IWF), Technical University of Berlin, have developed another approach, which is called EnergyBlocks. The approach is designed to assist engineers for planning and scheduling handling or assembly processes in order to optimize their energy consumption. The manufacturing processes are segmented into specific manufacturing operations, each with its specific energy consumption. The energy profile of every manufacturing machine, such as the machining center or transport system, is considered as input data for EnergyBlocks. Every operation state of manufacturing machines, e.g. "turned-off", "start-up", "warm-up", "stand-by", "processing" or "stopping" is described for creating an accurate energy profile for EnergyBlocks. Finally, to reduce energy consumption of the manufacturing process, the optimization of the manufacturing sequence and its EnergyBlocks is performed. The general concept of the approach is shown in Fig. 14.

The key factor to achieve accurate EnergyBlocks data is the data sources of the energy profile of every manufacturing machine, which in their approach is collected by mathematical modeling. Weinert, *et al.* [62] used the energy profile of a laser welding machine as the example here, which was further used to generalize the energy profile of every manufacturing machine. The generalization and assumption of energy profiles of every machine is useful when the engineer must deal with several manufacturing processes. However, this generalization leads to some drawbacks such as low-accuracy in the energy consumption prediction, especially for a manufacturing machine that has a wide range of operating conditions, such as IR. From this approach, they also found that the energy consumption of HS can be reduced by optimizing the operating state of machines. Since some machines are not on the “standby” state in many handling operations. It is thus recommended that a machine be switched to standby during a non-productive phase [63].

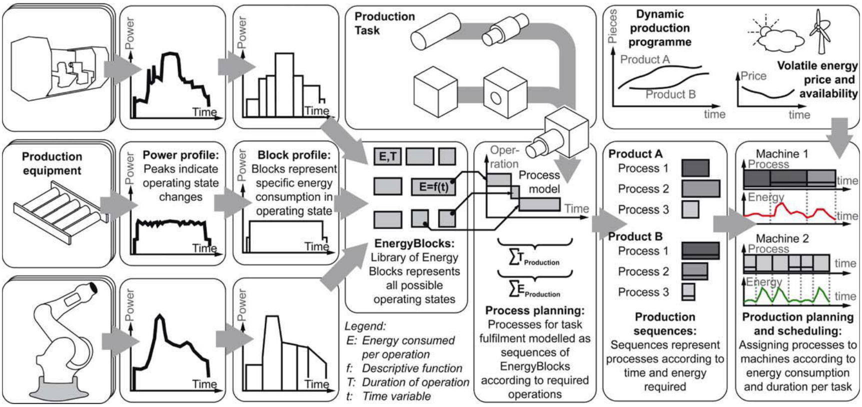

Figure 14: EnergyBlocks methodology [62]

Fraunhofer IWU’s approach

Researchers from the Fraunhofer Institute for Machine Tools and Forming (IWU) in Chemnitz propose a method that is used for predicting and optimizing the energy consumption of an automotive HS as well as its components. The approach focuses on the development of a control strategy for optimizing the energy-sensitive manufacturing execution systems (MES). The approach deals with the development of model-based manufacturing control strategies, which provide an optimal resource scheduling by means of energy visualization. Several software modules were developed in order to control and visualize the energy-flow in the systems [17].

They developed methods for reducing the energy consumption of machine tools and IR. An approach for the design of an energy-efficient machine tool is based on the study of bionics, drawing inspiration for technical designs from nature. By imitating natural structures, they designed lightweight machine tools [64].

For IR, the energy efficiency is improved by optimizing the robot path planning and its operation [65]. Although Fraunhofer IWU has developed a solution for energy-efficient HS, the analyzing and optimizing of the manufacturing machines is still limited. For instance, the energy profile of IR as part of automotive HS is mainly performed by experimental investigation and the application of the simulation tools is still limited.

Other approaches

The Institute for Factory Automation and Production Systems (FAPS) of the University of Erlangen-Nuremberg was developing several approaches for reducing the energy consumption of manufacturing systems. An expansion of a standard material flow simulation tool with energetic aspects, which is based on machines state dependent load profiles, was developed [66]. Using this expansion, it is possible to analyze real time conditions of energy consumption of automated production cells. The prototype of the concept is implemented in the *energy module* based on the simulation software Plant Simulation. The experimental validation shows that the developed model can predict the energy behavior of a fully automated manufacturing cell with an average deviation of 3.4%.

Furthermore, Institute FAPS was also developing an approach for predicting the energy consumption of production processes during the early phase of the development. The approach called *Methods-Energy Measurement* (MTM), which is combined with defined energy reference for manufacturing systems [6] [67]. Using this approach, key performance indicator and the basic energy consumption of machines are defined using empirical data from the reference processes. Therefore, it is possible to estimate the potential energy consumption of new manufacturing processes. A case study of an automotive body shop shows that MTM approach is able to predict energy consumption and energy cost of the process before the real system is constructed. Additionally, a method for energy efficient process planning of a manufacturing process was also developed by FAPS' researchers. The method is developed to minimize the energy usage of a factory by optimizing the manufacturing variables, e.g. material specifications, selected technologies, process and equipment selections. Based on optimization results, methods for assessment of the energy consumption of manufacturing systems can be defined. The developed method is called *E|Benchmark* [68].

The Institute for Machine Tools and Industrial Management (*iwb*) of Technical University Munich also proposes several approaches for production planning of an energy-efficient factory. For example, a planning method that focuses on the influence of the visualization of peripheral systems of manufacturing systems on employee behavior can be found in [69], while the energy reduction of the machines using an effective scheduling operation is proposed in [70]. Furthermore, a method for reducing the energy consumption of a factory by optimizing the flexible energy source is presented in [71] [72].

Beside all of the previous approaches that have been mentioned, several research solutions for process planning of an energy-efficient HS have also been proposed. Among these, a solution for planning and optimization of the energetic behavior of HS inclusive of the peripheral systems is proposed in [73]. In this solution, a HS and its machines are modeled and simulated using DES. Machine models are extended by involving energy information such as energy control loops and messaging systems. The result from the simulation is used as the basis to operate the HS. The solution is developed based on material flow simulation with further improvement on the machine state energy data, the information systems and its monitoring systems. The detailed description of the energy information of every machine state can be found in [74], while the energy consumption monitoring and control system can be found in [75]. These approaches seem powerful when implemented for the planning and optimizing of HS, but does not integrate with the kinematics and dynamics behavior of the manufacturing machines.

Modeling and optimization of energy consumption of production machines (i.e. machine tools) to optimize the energy consumption of the manufacturing process can be found in [76]. In this research, the energy consumption of machine tools is analyzed by defining several machine energy states, e.g. *machine off*, *run-up*, *stop*, *ready*, *active*, *spindle running*, etc. Then, the total energy consumption is calculated based on machining operations. For example, in a roughing operation, the energy profile of a machine tool is start with the *emergency stop* profile, *machine ready*, *axes-on*, *spindle-on*, *chipping* and ended with the *machine ready*. Here, the energy data of machine tools is used for planning and forecasting of energy-efficient machining processes.

The development of simulation platforms for prediction of the energy consumption is also used for real-time visualization of the energy use [74]. For other manufacturing machines, e.g. IR, proposals are found in [77] [2] [10]. In particular, several related works on process planning of IR, are presented in Sections 2.3.3 and 2.4.

2.3.2 Commercial and industrial solutions

Commercial solutions for analyzing the energy consumption of a HS as well as its kinematics and dynamics behavior are mostly based on modeling and simulation approaches. The commercial approach allows engineers to do manufacturing planning in a short period of time by developing a virtual manufacturing environment. Using these solutions allows manufacturers to market their products quickly as well as reduce their development costs [37]. In general, the current commercial solutions only analyze the kinematics and dynamics behavior of HS machines. Only a few of them involve the energy analysis in their system, while other software systems are still under development [2].

The following sub-section gives detailed accounts of commercial solution approaches for analyzing the behavior of HS which are currently available on the market.

Tecnomatix®'s approach

Tecnomatix® [78], which is developed by Siemens, is the leading simulation platform for planning and optimization of production and processes. Using this software, a manufacturing planner can model, simulate, visualize, analyze and optimize material flow, resources utilization and logistics of the production facilities.

There are two main software platforms from Tecnomatix® that can be used for process planning of a HS. They are Plant Simulation [79] and Process Simulate [80].

Plant Simulation is created based on a DES approach that allows planning engineers to perform experiments on the computer model without disturbing existing PS. This software is also commonly used in the planning process to analyze the material flow of the HS, which allows for optimization, e.g. by eliminating bottlenecks in the process [79]. Integrated with this software package is an IR simulation module called RobotExpert, which is mainly used for kinematics analysis of robot movements.

Due to the high demand of energy-efficient HS, researchers from Siemens, in collaboration with Fraunhofer IWU and Volkswagen, in 2013 developed an industrial simulation approach that integrated the traditional material flow simulation with energy modeling of individual components of HS [81]. Therefore, in this Tecnomatix® Plant Simulation software, there is the possibility to analyze the energy consumption of the manufacturing system together with the material flow simulation [82]. This approach has the advantage that it can predict the energy consumption of a HS before it starts production. The software can be integrated with EnergyAnalyzer module and therefore is able to analyze and optimize the energy consumption of the system.

In order to predict the energy consumption of the manufacturing machines, this software tool uses data of common manufacturing machines and then optimizes the energy state of machines in the production line. In other words, it reduces the energy consumption of HS by optimizing the state of the machine during production, whether it is at the state *off, standby, operational* or *working*. The case study shows that the simulation software was able to reduce the energy consumption of a door production line at Volkswagen by 10% without negatively influencing productivity [81]. The detailed concept of the Plant Simulation approach for simulated energy flow in PS can be found in [83]. However, because data of the manufacturing machines was collected from the specifications recorded in the manuals of the machines, the accuracy of the energy consumption prediction is low and/or the data is only accurate for general operating conditions. The specific energy simulation of handling machines cannot be analyzed at a higher degree of accuracy.

Process Simulate from Technomatix® can be used to analyze the energy consumption of HS that are used in the automotive industry, where they mainly consist of several IR. This energy tool is a result from the research project called *Green Car Body* [21]. The tool calculates the total energy consumption for a given time interval by breakdown of the energy profile of every robot, i.e. *movement* and *standstill* positions. In the standstill position, the energy consumption of the robot is further classified into *idle*, *brake-on*, *stand-by*, and *sleep* positions. Furthermore, the total energy of the robot is calculated as the sum of the manipulator energy, breaking resistor energy and cabinet energy consumption. The input data that is used for this tool comes from the robotics vendor, which includes ABB and KUKA. Thus, the accuracy of every value is the responsibility of the robot manufacturers. [84]

This software tools is still in the testing phase, with focus on how to provide virtual measurement capabilities. Meanwhile, the aim of energy reduction by optimizing the robot path planning is still under development [65]. This software is very useful for analyzing the energy consumption of HS as whole system but is limited to analyzing a single handling machine since the ability to count many energy losses is limited using this approach.

Other commercial approaches

Only few software tools are available for analyzing the energy consumption of HS, especially for process planning and optimization tasks. Many commercial solutions continue to focus on the kinematics and logistics analysis, e.g. Delmia [85], Visual Components [86] and FlexSim software [87]. For the planning task, Delmia from Dassault Systemes provides a comprehensive solution to support manufacturing processes, from planning and detailing to simulating the handling cycle [37]. Delmia's Assembly and Manufacturing Planning are able to validate the product design and define an assembly process. Furthermore, Delmia Process Planning (PRP) provides a virtual manufacturing environment of the HS and their processes. Therefore, the planners are able to analyze, optimize and validate the developed systems [85].

Another software tool that also provides 3D environments for planning, analyzing and visualizing a HS is Visual Components. The software offers the advantage of manufacturing machine libraries with components that can be added into 3D environments via drag-and-drop. Thus, it has the advantage of visualizing the HS, but is less suitable for comprehensive handling planning. Besides this, another example of software that focuses on the 3D environment is FlexSim developed by FlexSim Software Products, Inc [87]. This software tool also has the ability to visualize the assembly line. Similar to Visual Components, the focus of this software is on the kinematics, material flow and assembly space analysis. The energy analysis of HS machines is not included in this software tool.

Nevertheless, the energy consumption analysis can also be performed using other simulation tools. For instance, the energy modeling and simulation of HS using Colored-Timed Petri Nets can be found in [88], while Plant Simulation is used by [83] [89]. A further solution is based on a combined approach, i.e. by enhancing the capability of the material-flow simulation, which is proposed by [90]. Here, two possibilities for combining the material flow simulation with the energy consumption analysis are presented: the first one is by connecting two different software environments and the second one is by adding the energy module into existing software environments.

2.3.3 Energy-efficient industrial robots

The two previous sections deal with the process planning of the energy consumption of HS. In this section, the review is focused on IR as a component of the HS. The following approaches have been developed by researchers for process planning of IR.

ABB's approach

In terms of handling machines, i.e. IR, a simulation tool developed by ABB, and implemented on their IR software, is known as RobotStudio. The software is used for analyzing IR kinematics behavior, such as for collision detection and motion space analyses.

Since 2012, this software was embedded with a toolbox called Signal Analyzer that can be used to predict the energy consumption of ABB robots. It follows then, that it can be used not only to analyze the kinematics behavior but also to analyze the energy consumption profile of the robot at several operating conditions. As an example, the energy consumption of the RB4600 robot (60 kg version) at several operating speeds is shown in Fig. 15, which depicts the energy consumption in relation to the robot's execution time [91].

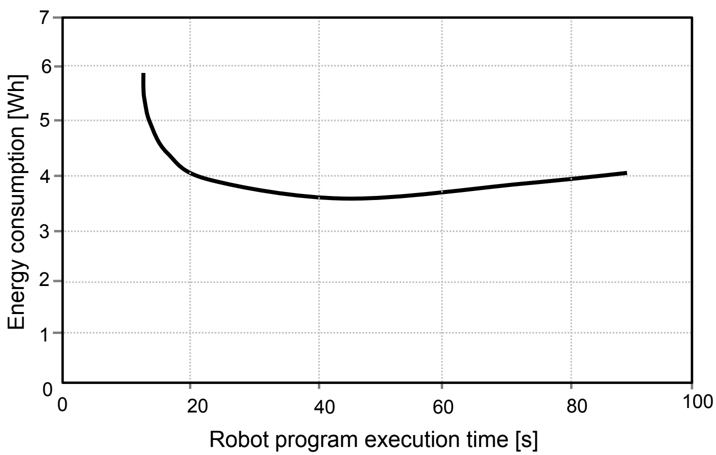

Figure 15: Energy consumption of IR in relation to the robot's execution time [91]

Signal Analyzer collects the energy consumption data of the robot from Total Motor Power signal. This signal calculates the power that used by the mechanical robot arm and not calculates the power used by the controller cabinet. The power that is fed into the controller cabinet is excluded. This is the reason why the simulation results of the robot energy consumption using RobotStudio is not precise. The investigation from [92] in 2014 found that energy data gained from RobotStudio is not consistent. They found a difference of 20% in energy consumption in two different simulations with the exact same robot trajectory. Thus, this result shows that the software tool is unwieldy for predicting the energy consumption of ABB robots.

RWTH's approach

Similar to RobotStudio, researchers from the Institute MMI, RWTH Aachen [93] developed a software tool that has the ability to analyze the energy consumption of IR at several path-planning conditions. The simulation application is primarily designed for aerospace applications since the robot has to contend with a limited energy supply within that environment. The simulation model is based on calculating the mechanical energy consumption of every motor of the robot axis [94], similar to the Signal Analyzer's works. Since the institute does not have a specific agreement with an IR company, the software is designed for a multi-platform robot. However, the accuracy of the simulation results is still limited due to many assumptions and simplifications in the simulation model, especially in the motor drive model. The real validation of the simulation model has not yet been conducted. Therefore, the accuracy of the developed tool is not yet known.

KUKA's approach

Similar to ABB, KUKA is involved in developing simulation tools that are able to calculate the energy consumed along a trajectory. The existing simulation tool that developed by KUKA, called KUKA Sim, is primarily used for analyzing the kinematics of the KUKA robot's motions by creating 3D layouts for systems with KUKA robots. Therefore, their approach is to develop a solution that is able to simulate manufacturing machines in the virtual world. The aim is then to calculate the total energy of the system. The simulation tool allows planning engineers to run various process scenarios to optimize their energy consumption [34]. However, the method how to collect the robot energy data is still not yet published. The accuracy of the simulation results is still largely unknown.

Fraunhofer IPA's approach

In 2013, Fraunhofer IPA and the Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW) in Stuttgart developed a modular simulation model of IR that can be used for energy planning of a manufacturing facility. The research conducted is part of a project called MoniSimO (Monitoring, Simulation and

Optimization of Robot Applications to Increase Energy Efficiency) [95]. The idea of this project is to develop a simulation model of IR for modeling, simulating and optimizing their energy consumption. The simulation model is used to optimize the operating parameters of the robot, such as the gripping and placement positions, and robot sequence. Furthermore, this simulation approach has the capability to store the recorded energy data of the robot, which is suitable to act as a basis for energy optimization.

Based on the description available from [96], the developed simulation model is useful for optimizing and reducing the energy consumption of IR, whilst in the planning phase. However, although the developed simulation model seems to be able to predict the energy consumption of IR, its capability to analyze the energy consumption and power flow of IR is limited. This is because the developed simulation model focuses on the analyzing of the energy consumption of IR with respect to their surrounding environments, with a limited exploration of the robot's internal components, such as the robot motor drives, control systems and mechanical structure. The idea of the developed simulation model is similar with existing commercial solutions that are provided by IR manufacturers, such as RobotStudio from ABB. These simulation models have shortcomings when analyzing the energy flow of an IR as a whole mechatronic system. Thus, the analysis of the influence of the robot's dynamics on energy consumption cannot be performed using these simulation models.

2.4 Methods for reducing the energy consumption of industrial robots

Data from the International Federation of Robotics (IFR) shows that robot sales have increased by 25% to 225.000 units in 2014 (see Fig. 16) [97]. This means that IR play an increasingly important role in the reduction of CO_2 emissions as well as in the reduction of operation costs, as more and more industries use IR in their HS.

Based on the author's previous publication [2], reduction of the energy consumption of IR can be achieved at several phases of HS development: at production planning, commissioning processes or at optimization stages (see Tab. 2). At the production planning phase, engineers are more flexible to define a strategy for reducing the energy consumption of the robots since the handling process and the needed machines are planned at this phase. Furthermore, engineers have the flexibility at this stage to choose the most efficient machine that will be used in HS. Therefore, the energy reduction can be achieved for example by choosing IR that have low energy consumption rates [98]. Besides this, energy efficiency can be improved at this phase by optimizing the IR's operating parameters and its operating conditions, as the productivity rate of the process is still to be determined in the planning process.

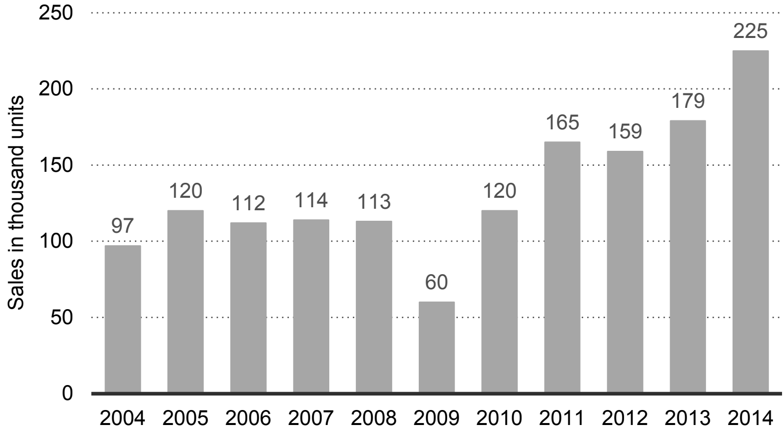

Figure 16: Estimated worldwide annual shipments of IR [97]

Table 2: Methods for reducing the energy consumption of IR used in a HS at several development phases [2]

Development phases	Example methods	Flexibility
Production planning	Defining IR operating parameter; choosing a low-energy-consumption IR	High
Commissioning process	Eliminating waiting time and reducing idle time	Medium
Process optimizations	Optimizing the IR trajectory; adjusting the IR's breaking time	Low

In the commissioning phase, which is used for checking and turning the installed machines, the energy reduction of IR can be performed by reducing idle time and eliminating waiting time of the robot [98]. By reducing the idle and waiting time, the energy consumption can be significantly reduced since more than 20% of robot operations are at these conditions [98]. However, in many cases, waiting time cannot be eliminated, thus optimizing the robot motion is more energy-efficient than shutting down the robot motor drive. At this phase, reducing the energy consumption of IR is restricted by many constraints, such as the handling rate and the robot specifications. Therefore, in this phase, the energy reduction is not as flexible as in the production planning phase.

For the process optimization phase, the engineer cannot change the robot's hardware apparatus, handling rate of the processes or the handling layout. Thus, limited methods for energy reduction are available that can be implemented in this phase and with stricter constraints. An example at this stage is the implementation of optimal trajectories or the releasing of the actuator brake earlier [99].

Every development phase of HS has several opportunities to reduce the energy consumption of IR. Choosing the best method which gives higher reduction results will lead to an effective and efficient development process. In this context, as mentioned in the Chapter 1, the production planning stage offers a significant energy reduction since many decisions are defined within this stage. Thus, this research is focused on this stage, i.e. on the strategy of reducing the energy consumption of IR by optimizing their operating conditions.

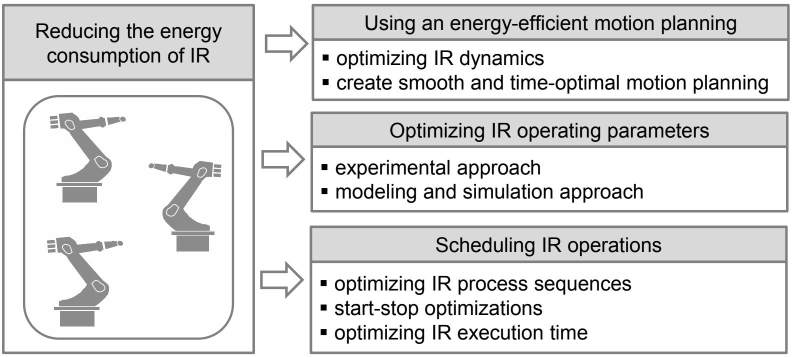

Figure 17: The research based methods for reducing the energy consumption of IR [2]

There are several methods that can be used by engineers for reducing the energy consumption of IR, as shown in Fig. 17. As shown in this figure, the application of energy-efficient motion planning can be performed by optimizing IR dynamics since the energy consumption is influenced by the robot dynamics parameters, as well as by smoothing the robot motion. Furthermore, the energy reduction of IR can also be performed by optimizing the robot's operating parameters. The optimization method is mainly decided by using the data that is collected via experimental or simulation investigation.

Another method is by scheduling of the IR' operation. Based on [98], this method is able to reduce the energy consumption of IR used in the body shop by 31%. Thus, the approach is very suitable for reducing the energy consumption of HS that have many IR in their systems.

Besides the aforementioned methods that are used based on research approaches, there are other methods also commonly used by engineers [2] [98] [100], e.g.:

- selecting low energy consumption IR that are suitable for a certain handling process,
- switching off the robot system over the weekend,
- going on standby mode for pause,
- reducing IR operating time, and
- using an intelligent mechanical brake system.

Another commercial method used is by implementing a new standard communication protocol that optimizes the energy consumption of the handling machines, such as by using *PROFIenergy* [101]. This method is easier to implement but has high investment costs in the beginning of the development. Beside this, many companies also visualize the energy consumption of every handling machine for improving the awareness of employees.

Despite the fact that several methods to reduce the energy consumption of IR have been developed, every method has its drawbacks and advantages. Using the energy-efficient motion planning of IR is able to reduce the energy consumption, but requires engineers to change the existing IR's hardware system and/or software. Thus, it comes with great effort and cost since most of the robot manufacturers don't have an option for energy-efficient motion planning [99]. Reducing the energy consumption of IR by optimizing their operating parameters is a new method. Based on the literature review of this dissertation, this approach has not been utilized extensively in research. However, without a modular model of IR, it can only be effectively used at the production planning phase, where the productivity rate of a handling process is planned.

The commercial and industrial solutions are limited for analyzing a specific IR model with focus on their environmental conditions. They have limitations in simulating the IR's internal components. A solution that can be used to analyze the kinematics, dynamics and energy consumption of the robot does not yet exist.

Among these methods, reducing the energy consumption of IR by optimizing their operating conditions is the most convenient method for a planning engineering since it is easily implemented and has a great influence on the energy consumption reduction. However to overcome the limitation of the experimental investigation, a modular model of IR is very advantageous, especially when optimizing the existing handling process is required, e.g. because there is a new process sequence or a new handling material.

More detailed literature review and the discussion about the existing methods for reducing the energy consumption of IR used in HS can be found in the paper that was published by the author in [2].

2.5 Concluding remarks

This section provides a summary concerning the existing approaches that are used for process planning of energy-efficient HS. The limitations of the approaches especially for predicting and analyzing the energy consumption of HS are listed. Finally, a solution is proposed that fulfills the requirements and resolves the issues that have been mentioned. The literature review, which has been given in the previous section, shows that research on the energy consumption analysis is a new trend in the field of manufacturing process planning, which aims to improve energy efficiency of the HS. Thus, the manufacturing paradigm has to be extended to not only focus on time, cost, quality and flexibility but also involve energy efficiency.

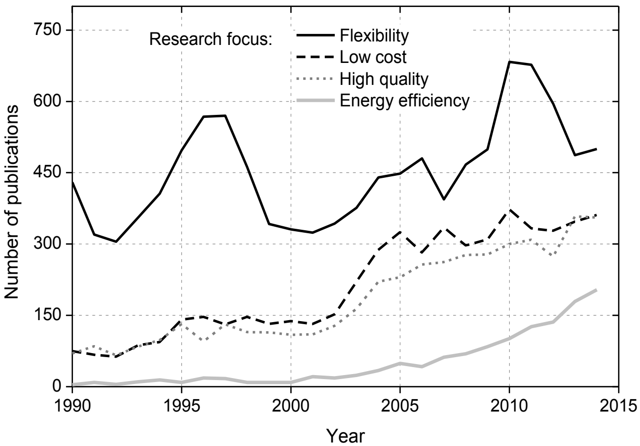

Figure 18: Trend of publications on the topic of manufacturing systems from 1990-2014[3]

The research evolution of manufacturing systems is depicted in Fig. 18, which shows the number of article publications that are indexed in Scopus database ranging from 1990 to 2014. This figure shows that research focused on the development of a flexible manufacturing system reached its peak in 2010, while research on the development of low cost, high quality and energy-efficient systems have been increasing steadily. Particularly, since 2006 the number of publications on the topic of energy efficiency has increased exponentially. With regards to this, the current handling process planning research, which commonly uses simulation approaches,

[3] Data is collected from Scopus (www.scopus.com) with limit to the articles that belong to the engineering field, access date: November 19th, 2015.

should address not only the kinematics and dynamics behavior analyses but also the energy consumption analysis.

This chapter also presents a short review of the existing methods for reducing the energy consumption of IR used in HS. The discussion of the existing solution method is presented based on the author's article [2], which aims to give a clear discussion on the advantages and disadvantages of every existing method. An optimal solution for energy reduction is a combination of several proposed methods. However, using the simulation approach will lead to better energy consumption reduction, especially in the process planning and optimization stage.

Moreover, based on the literature review, the author believes in the importance of collecting, analyzing and optimizing the energy profiles of handling machines for process planning of an energy-efficient HS. Most existing solutions are focused on the production line or factory levels. The acquisition of detailed energy profiles and strategies for optimizing the handling machines are still limited and largely unknown. Thus, developing a simulation approach to address this challenge will improve the energy-efficiency of the HS and the factory as a whole system. In addition, the existing process planning approaches do not combine the energy estimation with the kinematics and dynamics analysis. Therefore, an integrated simulation approach that can address not only kinematics and dynamics analysis but also energy consumption analysis is desired.

Limitations of the current solutions

Research on the development of the manufacturing process planning has been performed for many years. However, due to the complexity of its requirements, many problems have not been solved yet. Based on the literature review, the following limitations of the current manufacturing process planning approaches are given.

- Most of the modeling and simulation approaches are limited to only kinematics and dynamics behavior analysis of handling machines, that is, they are not integrated with the energy consumption simulation.
- Current industrial simulations, which are used in the process planning and optimization of HS, are primarily focused on material flow, kinematics and logistics analyses to optimize system productivity. The approach to integrate the whole mechatronic behavior in the process planning and optimization of handling machines is still limited.
- In current practices, limited energy data is considered in process planning of HS. Several researchers have proposed new energy planning ideas, but they commonly use energy data from historical measurements or product specifications, which are limited by their accuracy and only valid for specific machine states. Thus, the energy consumption of handling machines cannot be analyzed according to its real operating conditions.

- Handling machines have a great impact on the energy consumption of factories. Therefore, optimization of the energy consumption of handling machines will lead to an energy-efficient PS. However, current research is still limited, focusing primarily on machine tools.

Commercial industrial simulation tools, such as Plant Simulation and Process Simulate, can be used for analyzing energy consumption of HS by optimizing the state and the sequence of the machine, but have limitations with regards to the analyzing of the relationship among machine parameters and dynamics behavior of the handling machines.

The proposed solution

Literature of the recent methods concerning process planning of HS and their drawbacks has been presented in the previous sub-section. After carefully surveying these methods, this dissertation proposes a mechatronic simulation approach that can be used for the process planning of HS. This approach involves the analysis of the mechatronic behavior, such as kinematics, dynamics and energy usage of handling machines. The solution deals with multi-domain simulation approaches that are used to support and predict the mechatronic behavior of every manufacturing machine, since an energy-efficient HS can only be achieved when the energy consumption of handling machines is predicted with sufficient accuracy.

Furthermore, energy data of every machine is analyzed in order to optimize their operating parameters. The mechatronic simulation concept, which is based on object-oriented and multi-domain simulation, is suitable for behavior analysis of the mechatronic systems and also can be used to analyze the relationship among the domains of the systems. Next, accurate simulation models of handling machines, focusing not only on the surrounding environment but also on the detailed model of every machine, are developed (as shown in Fig. 1). As a case study, a detailed investigation of an IR, a commonly used HS machine, is conducted in this dissertation.

3. Mechatronic Simulation as the Basis for the Process Planning of Energy-Efficient Handling Systems

In order to analyze the system behavior of HS, engineers usually perform an experimental investigation. However, under practical considerations, an experimental investigation is associated with some issues such as high costs, high safety requirements and long experiment time. Thus, simulation methods are commonly used for the process planning of HS. This is due to their ability to reduce development time and improve the performance of the complex HS. However, common simulation tools on the market primarily focus on the kinematics and dynamics behavior analyses of the handling machines without involving their energy consumption behavior. Therefore, a simulation approach that can analyze the energy consumption behavior of the handling machines is proposed here.

This chapter describes the mechatronic simulation approach for the process planning and optimization of a HS machine. Firstly, the chapter presents the scope of the mechatronic system behavior. Subsequently, the description and application of the object-oriented and multi-domain simulation paradigm as the basis of the mechatronic simulation are given in Section 3.2. Next, the integration of mechatronic simulation in the process planning of handling machines is presented, with emphasis on the analysis of the energy consumption. Finally, a summary and other remarks are given at the end of this chapter.

3.1 Scope of the mechatronic simulation analysis

Historically, the term mechatronics, which appeared for the first time in 1969, was coined by Japanese engineer Tetsuno Mori from Yaskawa Electric Co. At this time, mechatronics was simply the combination of mechanics and electronics, i.e. the word is a combination of "*mech"* from mechanics and "*tronics"* from electronics [102]. Since then, automation systems have increased in complexity, and the term mechatronics to date involves at least mechanics, electronics and informatics.

In the first development stages beginning in the 1860s with the creation of the steam engine, mechatronic systems mostly consisted of pure mechanical systems. At the time, technologies used in control systems were still limited while components were developed rather independently and individually without collaboration. At the beginning of the 20th century, the development of electrical drives increased, application of DC and AC motors in industries lead to the development of mechanical systems with electric drives. At the time, several mechanical products were integrated with electric motors, such as machine tools, pumps and mechanical typewriters. Sequentially, factors like increasing automatic control, the invention of the computer and the increasing of cyber-physical systems lead to the development of complex mechatronic systems. [103]

Mechatronic systems are applied more and more often in several different business sectors like automotive systems, industrial products and consumer goods. For example, in manufacturing industries, most of the handling components are mechatronic systems. As a result of this, mechatronic systems have a major role in this field. Based on new data from [104], the complexity of mechatronic systems has been dramatically increased; doubling every 2-3 years.

Thus based on aforementioned description, mechatronic simulation refers to simulation tools that have the capability to simulate the system behavior of the mechatronic product, e.g. dynamics behavior, control behavior and pneumatics or hydraulics behavior (see Fig. 19). Simulating these behaviors cannot be done separately since they are all interdependent. Optimization of one of the specific behaviors will affect the others. For example, optimizing the control behavior of the mechatronics will automatically change the dynamics behavior of the system. Because of this, simulating and analyzing the mechatronic behavior will give a comprehensive solution to improve the performance and efficiency of the systems.

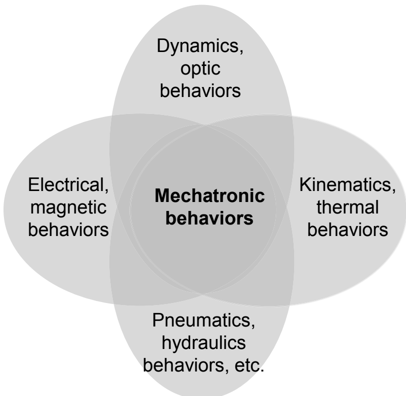

Figure 19: Scope of the mechatronic behavior analysis

In the research presented here, the mechatronic simulation approach focuses on analyzing kinematics, dynamics and energy consumption behavior of handling machines such as IR. These behaviors are further elaborated upon in the following sub-section:

Kinematics behavior analysis

Kinematics is categorized as the part of classical mechanics that is concerned with the study of motion without considering the cause of motion itself. The object of kinematics studies can be a point, a line, bodies/structures, or a system of bodies. In other words, kinematics describes the behavior of multibody systems in motion, velocities and accelerations of the trajectories of points, lines and other geometric object properties. This allows for the simulation and analysis of steady-state motion, without considering forces involved. [105]

In process planning, kinematics behavior analysis is useful for analyzing spatial constraints of systems such as displacement, velocity and acceleration for every design concept, as well as for analyzing handling sequences. Rough CAD-models are usually used to support the kinematics analysis to give better visualization and documentation [106], in order to visualize possible incidents of collision among components and optimizing the workspace of the factory.

Dynamics behavior analysis

In contrast to kinematics, that studies the motion of bodies without reference to its cause, dynamics is concerned with the study of force and torques as well as their effect on a body's motion [107]. Thus, dynamics analysis of bodies is more complex than kinematics analysis since it must consider other quantities such as mass, inertia, force, torques as well as displacement, velocity and acceleration. In HS, dynamics studies are used to analyze system behaviors of handling components in order to optimize their performance. The scope of the dynamics study is mostly focused on the torque, velocity and acceleration of each handling machine.

In most cases, dynamics analysis is not performed in the process planning of HS. Instead, engineers use data from product specifications derived from machine manufacturers. As a result, most handling machines do not operate at optimum levels of performance. Therefore, by analyzing dynamics behavior of a HS's machine according to its real-world processes, engineers can improve a system's performance, thereby reducing the operating cost and the energy consumption.

Energy and electrical behavior analyses

In the traditional process planning of HS, analysis of the electrical behavior of handling machines are not conducted, i.e. the energy consumption and electrical specifications such as the energy profile, electricity current, voltage and power are not analyzed in the early planning stage. Based on this fact, the mechatronic simulation presented here will include an electrical behavior analysis, which will be integrated with the kinematics and dynamics behavior analysis in the planning of HS.

Furthermore, the mechatronic behavior analysis also deals with other system behaviors such as pneumatics, hydraulics and control system behavior. These behaviors are also key factors to improve the performance of the HS due to the potential advantages to be gained from improved efficiency, flexibility, the development schedule and reduced operating costs.

In this dissertation, these behaviors are included in the analysis. For example, in the IR performance analysis, kinematics, dynamics and energy consumption behavior is included in the discussion of the simulation results.

3.2 Fundamentals of the mechatronic simulation

In this section, the mechatronic simulation for analyzing the systems behavior of handling machines is introduced, which is presented in Sub-section 3.2.1. The object-oriented and multi-domain methodology that it is used as the basic of the mechatronic simulation paradigm is presented in the next sub-sections. Finally, the available mechatronics simulation tools and system modeling methodologies are presented at the end of this section.

3.2.1 Introduction to the mechatronic simulation

Mechatronic simulation is a simulation approach that deals with integration of several mechatronic domains, like mechanics, electric and control into a single simulation environment. Therefore, it is able to analyze the system behavior of complex mechatronic systems, such as IR, as a whole system. The difference between mechatronic simulation and common simulation approaches is its ability to model, simulate and analyze all system behaviors that are included in the scope of the mechatronic domain; normally, simulation tools are only able to simulate one or at most two domains of a mechatronic system.

A simulation itself is a set of techniques, methods, and tools for performing an *experiment* using the simulation *models* to study the *systems* behavior [108]. It also can be said that a simulation is an approach that tries to imitate real conditions within a computer simulated environment to study the systems behavior (see Fig. 20). Based on this definition, it can be concluded that the simulation approach requires the description of three terms, which are *system*, *experiment* and *model.*

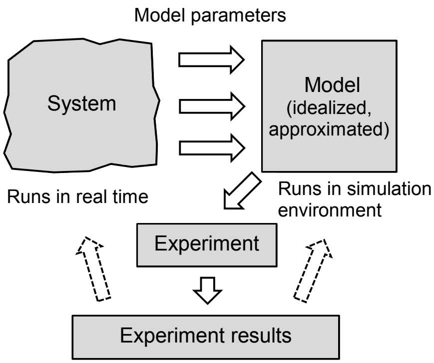

Figure 20: The concept of a simulation approach (based on [109])

Based on [108], "*system is an object or collection of objects whose properties we want to study*". Thus, a system can occur naturally (called *natural system*) or artificially (called *artificial system*). In regards to the HS or almost any engineering system, the term *system* is artificial. Studying a *system* of handling machines can be used to optimize their performance and their energy consumption.

An *experiment* is a set of procedures performed with the objective of extracting information from a system or for verifying a hypothesis. To perform an experiment on a system, the input parameter must be controllable and observable, a condition which can be difficult to accomplish. Furthermore, in many complex engineering cases, there are several problems that need to be addressed in order to perform the experiment, for example [10] [108]:

- performing an experiment might be too dangerous, such as an experiment in a dangerous environment or in a radioactive atmosphere.
- cost for performing an experiment might be too high.
- the system does not yet exist for conducting the experiment. This happens when the system has not yet been designed or manufactured. For example at the HS planning phase, no existing systems are available. Therefore, an experimental investigation is not possible.

Based on the definitions of *experiment* and *system*, a *model* can be anything that is used to mimic a system in order to analyze the system's properties and behavior. Thus, by applying the use of a *model*, an *experiment* can be performed without a *real system*.

Models can take the form of a mental model, verbal model, physical model or mathematical model. In engineering, the last two model forms are commonly used. A physical model is a physical object that imitates some main properties of real systems, which are then used to evaluate that system. For instance, the physical model of IR is commonly created to analyze real features and their kinetics behavior. A mathematical model is a mathematical equation, which consists of variables, whose relationships describe system behaviors. Variables such as mass, length, size and temperature are expressed in mathematical equations. For example, Newton's law is a mathematical model to describe the relationships between mass, acceleration and force. Ohm's law describes a mathematical model for relationships between current and voltage in a resistor. [108]

A simulation approach offers many advantages in the process planning of HS, as mentioned in Chapter 2. However, a simulation approach should also be used with caution, and the following points highlight the possible pitfalls when using a simulation approach for HS simulation [108]:

- *Falling in love with a model, called the Pygmalion[4] effect.* Simulation engineers easily focus on simulation itself and neglect the real condition of systems. Simulation engineers may forget that a simulation model is just a representation of real conditions, which is created with some assumptions and approximations.
- *Forcing reality into the constraints of a model, called the Procrustes[5] effect.* In the development of a simulation model, an engineer may define constraints that might not be suitable for real conditions or may neglect several main conditions that should be involved in a simulation model.
- *Forgetting the model's level of accuracy.* It is normal that every simulation model has simplifications and assumptions. Therefore, engineers have to be aware of those conditions in order to avoid misinterpretation of the simulation results.

In order to avoid all these simulation dangers, simulation engineers are suggested to not only focus on the simulation conditions but also consider the real application. In view of this, experimental investigation both to validate the simulation results and to get the feel of the real system is mandatory.

3.2.2 Object-oriented modeling and simulation

A convenient way of modeling mechatronic systems is using an object-oriented modeling approach. This approach is particularly suited for engineers that do not have a deep background in programming. Based on [111], the term "object-oriented" does not only mean modeling with objects, but also "*follow[s] the characteristic object-oriented approach, including encapsulation (hiding internal detail), message-passing, inheritance (from class to subclass) and polymorphism (the same procedure can operate on different data types)".*

This mean that the idea behind object-oriented modeling is to develop a mathematical or physical model based on equations inside the model or sub-model that is represented by an object. Therefore, in order to use object-oriented modeling, engineers must try to understand the structure and decomposition of systems [108]. To create a model using an object-oriented approach, the following steps should be adhered (see Fig. 21).

---

[4] In Ovid's narrative, Pygmalion was a Cypriot sculptor who carved a woman out of ivory and named her Galatea, a young woman. Because his statue was so fair and realistic, he fell in love with it and asked god to make it alive. [110]

[5] In Greek mythology, Procrustes was a rogue smith and bandit from Attica who physically attacked people by stretching them or cutting off their legs, so as to force them to fit the size of an iron bed. [110]

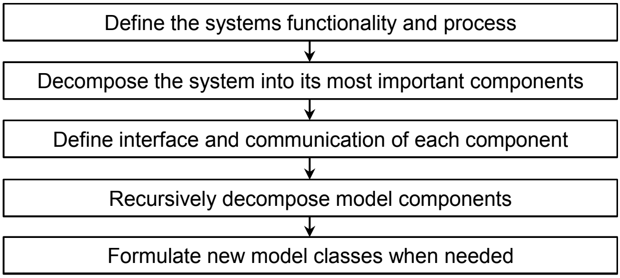

Figure 21: Phases in the development of object-oriented simulation models (based on [108])

The first phase in the development of an object-oriented model is defining systems that will be modeled, with regards to its functionality. For example, in the modeling of IR, this step includes defining the robot's main functions and processes. The next phase is decomposing the systems into several main components. In the IR, the main components are the robot structure, robot motor drive and robot controllers (see Fig. 22). Next, the connection type of each main component is defined. For example, the connection between robot controller with robot motor drive and between robots structures with their motors. After the main components are defined, the next phase is decomposing the components into several sub-components. Finally, define the equations and physical phenomena of every model class.

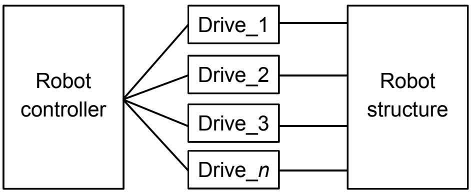

Figure 22: Schematic picture of connection diagrams for IR

In engineering, the oldest object-oriented modeling approach is Bond-graphs. Further along the line came the development of SysML, MATLAB Simulink® and Modelica®-based simulation tools, e.g. Dymola, SimulationX, and Wolfram SystemModeler®. The latter are not only object-oriented software, but also use an *acausal* approach. This is very applicable to engineers since it facilitates the reuse of components and the evolution of models [112]. Especially in terms of HS, object-oriented models offer some advantages over traditional modeling practices, as can be seen in Tab. 3.

Table 3: Comparison between traditional modeling and object-oriented modeling for simulating HS (based on [113])

Factors	Traditional modeling	Object-oriented modeling
Model construction:		
Software	Simulation languages based on procedural programming style	Simulation environments based on object-oriented programming style
Translation into code	Process is abstract	Process is natural and intuitive
Interface	Usually textual	Usually graphical with icons and dialog boxes
Level of detail	Usually not much detail due to programming complexity	At user's discretion, but requires detailed object library
Treatment of distinct systems elements	Different element types are not distinctly modeled; aggregation to reduce program complexity	Physical, information and decision/control elements are modeled distinctly and independently
Effort/time/cost	Moderate costs of model development, but a "throw-away" type	Initial cost of establishing detailed model is very high, but costs of subsequent reuse is low
Model attributes:		
Purpose	Usually a unique model is created for a specific purpose	More general models possible for multiple purposes
Usage	Single usage, throw-away models	Repeated usage and continuous refinement
Flexibility	Highly inflexible; changes almost always result in a complete rewrite of program	Highly flexible, due to the ability to modify fundamental building blocks; quick reconfiguration is possible
Accuracy	Useful for measuring relative differences in alterative configurations	With greater degree of detail and realism, can also estimate absolute performance with greater accuracy

Based on the comparison in Tab. 3, the object-oriented simulation approach seems more suitable for simulating handling machines, both in model construction and model attributes.

3.2.3 Multi-domain simulation paradigm and tools

Multi-domain modeling is a simulation approach that combines several physical domains of the systems into single simulation models. A multi-domain simulation model is constructed with components from several domains, which is mostly needed when developing and analyzing the mechatronic systems [114]. The multi-domain simulation environment must deal with mechanical, control, electrical and other physical domains and the interaction among domains should be easily seen.

This multi-domain requirement can be fulfilled by representing all mechatronic components in mathematical equations, using an *acausal* approach. By equation modeling, communication among domains is possible since the physical behavior of each domain is represented by equations. As an example, multi-domain modeling using equation modeling is depicted in Fig. 23, which shows the connection among several domains in an electrical motor model. Each behavior of the motor components is represented by mathematical equations. Therefore, it becomes possible to determine the relationship between the electrical components (e.g. resistor, inductor) and the inertia of the motor via an electromotive force (EMF) equation, which shows the relationship between the change in electricity as the input and the rotation as the output.

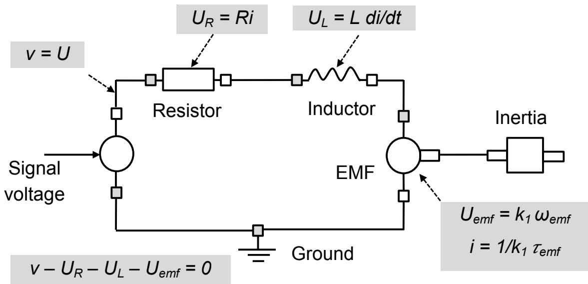

Figure 23: Defining classes and basic equations for a simple electric motor (based on [108])

The main issue of developing a multi-domain simulation model is defining the interfaces and connections among components. Each component has to be able to communicate with other components or subsystems according to its natural/defined communication structure. This requirement needs a model developer that has the capability to design or choose connection classes appropriately. In several multi-domain simulation tools, the connection classes are defined, with those commonly used including Positive or Negative Pin, Digital Input/Output, Flange, Signals Input/output, etc. Understanding the connector classes is an important task in order to design an appropriate components interface. Based on [108], the following requirements should be followed to create a new connection class:

- The interface of the developed component should be *"easy"* and *"natural"*, in order to create a connection between components. This means that the interfaces have the same behavior as the real systems.
- The developed interface should fulfil the criteria "*reusability*" and can be stored in a model library as a class.

There are many multi-domain simulation tools that are available, both commercial and open source software. Based on [115], the available software is shown in Tab. 4. Since every simulation tool and modeling language offers its advantages, choosing the right simulation tool or modeling language to perform a simulation experiment is an important task.

Table 4: Simulation tools for multi-domain simulation analysis (based on [115])

Simulation tools	**Field of application**	**Salient features**
Dymola	Mechanical, electrical, hydraulic, pneumatic, thermal, thermodynamic, control system, mixed systems	Mechatronic modeling; non-causal and object-oriented modeling; built upon Modelica® language
Simulink	Electrical system, control system, mechanical system, thermal system	Supports linear and non-linear systems; modeled in continuous, discrete and hybrid time; causal and object-oriented modeling
Simplorer	Electric, thermal, electromechanical, electromagnetic and hydraulic	Integrates multi-system modeling techniques including circuits, block diagrams, state machines, equation levels and modeling languages (VHDL-AMS, Simplorer Modeling Language, C/C++)
COMSOL	Electrical, thermal, electromagnetic field, fluid flow, structure mechanic	FEA-based software for various physical and engineering applications
ANSYS	Mechanical, structural mechanic, electromagnetism, fluid dynamics	FEA-based modeling that is able to perform mechanical structure and behavior analysis
MathModelica	Mechanical, thermal, electrical, control, hydraulics, bio-chemical	For engineering and life science modeling; object-oriented and non-causal modeling

TRANSYS	Electrical and thermal analysis, solar thermal and PV, low-energy buildings and HVAC systems	Simulation for dynamics behavior of an energy system, modular nature and allows custom mathematical models
MagNet	Electromagnetic field, electro mechanical	FEA tool for simulating electro-magnetic fields
PLECS	Electrical, electronic and thermal	Simulates semiconductor devices and their thermal losses
JMAG	Electromechanical system	Finite element-based program for modeling electro-mechanical energy systems
AMESim	Hydraulic, pneumatic, electrical, mechanics, electromechanical, thermal	1-D simulation tool for analyzing multi-disciplinary behavior, validated with analytical models
MapleSim	Mechatronic, machine design, control design, electronic, HIL testing	Object-oriented modeling and simulation; non causal; mechatronic simulation
INSEL	Solar energy, thermal collector and meteorological	Simulation tools for PV generator
VisSim	Electrical, mechanical, thermal, control and communication	Dynamics simulation tool for linear, non-linear, discrete time, continuous and hybrid system design
CASPOC	Electrical and drives, control systems, mechanical system	Power electronic modeling and simulation

Identification of the available tools as shown in Tab. 4 will lead to a better understanding and an improved decision-making process. Based on Tab. 4, the leading simulation tools that deal with multi-domain simulation capabilities are tools that use the Modelica® language as their platform, such as Dymola, SimulationX, MapleSim™ and Wolfram SystemModeler®. Therefore, in this dissertation, Modelica® is chosen as the modeling language that is used for developing the simulation model of handling machines.

3.2.4 System modeling of mechatronic simulation

In the development of mechatronic models, there are two well-known methodologies, which are top-down and bottom-up modeling. The decision to apply one of these methodologies depends on the engineer's knowledge concerning systems that are to be investigated. Top-down methodology can be applied to systems for which there are model libraries available to construct the model of the systems. In this case, engineers construct system models by defining its top-level model; continue to decompose this into several subsystems, until the basic component of a subsystem that is available in the model library is found. [108]

When systems to be investigated are new and less well known, or for which no model libraries are available, the bottom-up modeling approach is more appropriate than top-down modeling. Bottom-up methodology starts with the development of basic component models of systems and the analysis of their behavior. As the next step, further components are developed based on the most important model behavior. Based on several basic component models, subsystem models can then be constructed. Similarly, other subsystems are constructed. Using these subsystems, engineers construct a model that represents the whole system to be analyzed. [108]

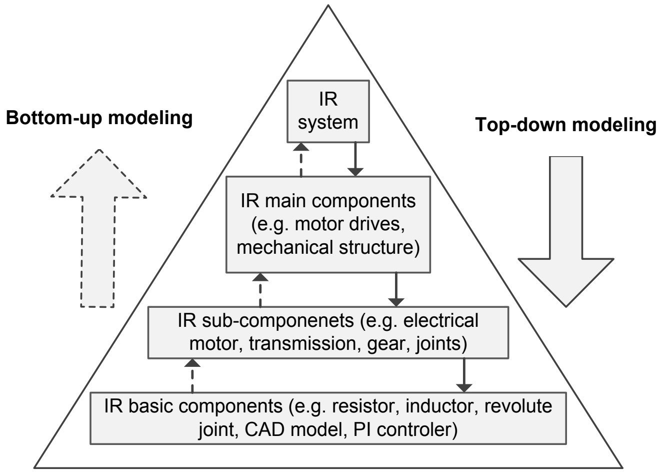

Figure 24: Top-down and bottom-up modeling methodologies for developing an IR simulation model

These two development approaches are depicted in Fig. 24. In this research, the handling machine is modeled using a combination of the two aforementioned methodologies, i.e. top-down and bottom-up modeling. This is because not all of the IR' basic components are available on the Modelica® Standard Library (MSL), or existing Modelica® models are not applicable for the real components in this study. Therefore, some of the basic components' models need to be defined and created.

3.3 Mechatronic simulation for energy consumption analysis: Concept and system requirements

Involving the mechatronic simulation for the process planning of handling machines in order to analyze their energy consumption, kinematics and dynamics behavior will lead to the development of energy-efficient and high performance HS. As mentioned in Sub-section 3.1.3, a mechatronic simulation tool can simulate the electrical behavior of the system components, e.g. an electrical motor drive. The electrical parameters such as current, voltage and resistance can be collected. Thus, it is possible to calculate the power and energy profile of a handling machine along depending on their operational condition. Using this concept, the energy profile of a handling machine is analyzed. Therefore, analysis of the electrical behavior and energy profile of the system in several operating conditions is possible. The overview of the concept is depicted in Fig. 25.

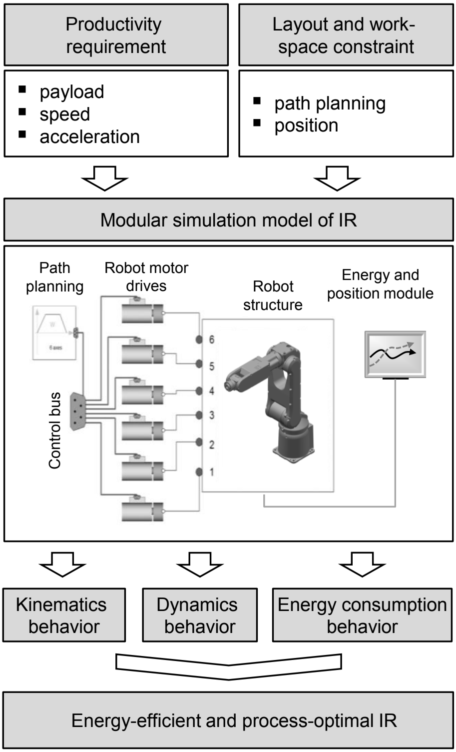

Figure 25: The mechatronic simulation approach for analyzing kinematics, dynamics and energy consumption of IR

An IR, as part of a HS, is modeled based on the input conditions, such as productivity requirement, lay out constraint, and work space. The parameters that belong to the productivity requirement are payload, speed and acceleration. Further, the parameters and condition of path planning, collision, position and working space belong to the layout constraint. These parameters are then used as the basis for modeling of the IR dynamics model. Therefore, using the developed simulation model, the influence of these parameters on the robot energy consumption can be analyzed.

Furthermore, by using object-oriented and multi-domain modeling simulation tools, a modular IR model is developed for energy examination purposes as well as for dynamics and kinematics analyses. The modular robot model consists of path planning, robot motor drives, robot structure and the energy and position module. The robot path planning is used to give instructions for the robot model to move to a defined position at a specific speed. The robot drives are used to actuate the robot manipulator arm, which consists of six arms and joints. To visualize the power and energy consumption, as well as the position of the robot's axes, the energy and position module is developed. Detailed description of the IR robot model will be presented in Chapter 4.

From the simulation results, an energy consumption analysis is performed using data of the electrical and dynamics behavior of the robot. Therefore, an energy profile of IR at several operating conditions can be monitored and visualized together with its kinematics and dynamics behavior.

The general research and experimental investigations are depicted in Tab. 5.

Table 5: Research methodology and its applications

Research conditions	Explanation
Simulation tools	Modelica®-based simulation tools, especially Catia Systems Engineering; another Modelica® tools that are also used is SimulationX
Case study	The IR as part of the UCM cell. The UCM is a comprehensive test platform for testing electronic devices (e.g. PCB)
Focus of the analysis	Operating conditions of the IR, i.e. a Motoman MH5L; another study on IR is also conducted on an ABB IRB6620 but not presented in this dissertation (see [116] in detail)

In this research, Catia Systems Engineering is chosen as the multi-domain simulation tool, with the case study on the electronic production HS called UCM cell (as shown in Fig. 26). The UCM cell is a HS platform that is used as a comprehensive test platform for testing electronic devices, for example controlling and checking the circuit of a printed circuit board (PCB). This cell consists of four main components: a Motoman MH5L robot with a special gripper, conveyor systems, hot test module and two UCM test platforms for in-circuit testing. The robot in this cell is mainly used for handling PCBs from one module to the other (see Fig. 26c). In this research, the robot is used as a handling machine of a handling cell that is a part of an electronic production facility (see Fig. 26).

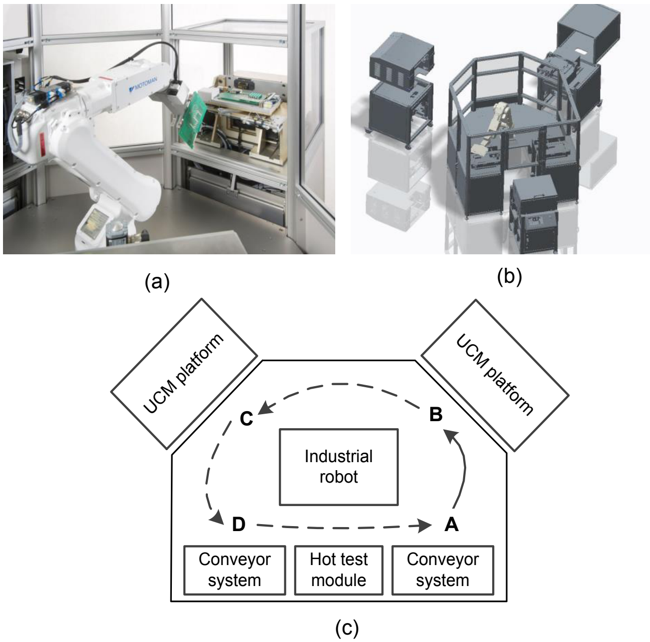

Figure 26: (a) The configuration of the UCM cell, (b) the 3D model and (c) the robot cycles (design by IMAK GmbH)

In order to implement the mechatronic simulation approach into process planning of the HS, the following requirements should be considered in the development of the IR simulation model:

- the robot model should fulfill the modularity aspect, which means that it can be used for simulating several IR models,
- the model should be developed based on the object-oriented and multi-domain simulation paradigm in order to reduce the complexity of the model for easy use,

- has the ability to visualize the robot movement in 3D model for kinematics analysis purposes,
- the model should have the ability to analyze the power and energy consumption of IR at several operating conditions.

3.4 Concluding remarks

This chapter provides a modeling approach that can be used for process planning of IR by analyzing their energy consumption behavior as well as their kinematics and dynamics behavior. Integration of mechatronic simulation approach into process planning of handling machines is proposed to overcome the drawback of the current simulation approach, which is limited involve an energy consumption analysis. In this chapter, the scope of mechatronic simulation, fundamental knowledge and the concept of applying a mechatronic simulation for process planning of energy-efficient handling machines are presented. The ability of mechatronic simulation to integrate the entire domain of mechatronics systems enables kinematics, dynamics and energy consumption analyses, which can be done in one simulated environment. Therefore, it is suitable for the process planning of handling machines, which includes kinematics and dynamics analyses, energy consumption prediction and the evaluation of machine control systems.

The detailed description of the fundamentals of the mechatronic simulation approach is presented in Section 3.2, which includes the object-oriented and multi-domain simulation approach, mechatronic simulation system modeling and the available simulation tools on the market. Furthermore, the research methodology and the research conditions are presented in Chapter 3.3 that describes the simulation concept and application of the proposed approach.

By using the developed approach, planning engineers can be expected to reduce the energy consumption of HS by the following ways:

- make an accurate prediction of the energy consumption of IR, in order to estimate the energy cost of the IR' operation, thereby allowing then to choose the best energy reduction strategy, e.g. by optimizing the operating condition of machines with respect to their energy consumption,
- define a strategy to solve new challenges in PS, i.e. flexibility in the energy supply that is caused by use of renewable energy sources.

4. Modeling of the Industrial Robot Using the Mechatronic Simulation Approach

As previously mentioned, IR consume up to 50% of the total energy in handling processes, e.g. in body shop processes. Therefore, in this research, the focus is on the analysis of IR due to the huge potential for reducing the energy consumption of HS.

This chapter presents the modeling method of IR using a multi-domain simulation tool for analyzing its mechatronic behavior. The simulation tool, Catia Systems Engineering, which includes the Modelica® language, and SimulationX are used for model development and analysis purposes. Furthermore, the chapter also describes the fundamental theory of the dynamics behavior of IR and their components as a basis for creating the simulation model. The six-axis IR, Motoman MH5L, was taken for the case study analysis.

4.1 General structure of the industrial robot simulation model

The International Organization for Standardization (ISO) defines an IR as "*an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications*" [117]. That definition shows that a common IR system consists of mechanical structures, actuating drives, sensors, power supply and a control system.

The mechanical structure of an IR comprises robot links and an end effector. The common mechanical structure of IR can be classified into closed and open-loop kinematics. Closed loop kinematics (also called parallel kinematics) are robot mechanisms where the links and joints are configured such that at least one close loop exists [118]. An example of a typical implementation of this is the Stewart platform. In contrast, an open-loop kinematics is a mechanism in which the links are configured such that no closed loop exists, e.g. six-axis IR. In this research, the focus of the investigation is on open-loop kinematics.

Another main component of IR is the drive system that is used to move or rotate the links into their determined positions. This can be achieved using electric, hydraulic, or pneumatic power, but electrical motor drives are commonly used. Likewise, electrical motor drives are used for the modeling of six-axis IR.

A major component of the IR model is the control system, which is the "brain" of the robot, whose function is to give instructions for robot motion as well as to control the operating conditions of the robot.

As described in Chapter 3, there are several simulation tools for modeling and simulating IR. The best choice is the simulation tool based on the Modelica®

language, which uses an object-oriented approach. Modelica®-based simulation tools are capable of modeling the internal components of robots and combining all of these components into an integrated system. By modeling the internal components of IR, it is then possible to analyze the relationship among these components in order to get a better understanding of the systems. Specifically, it makes it possible to evaluate the power flow of the IR. Furthermore, Modelica®-models can be interpreted as classes, which are described by differential and algebraic equations to represent the physical behavior of each model. Therefore, an IR model can be created by connecting several classes, which can be done manually through mathematical code or via connecting elements in a block diagram. In order to support the model developer, a variety of classes representing commonly used devices in engineering is available in the MSL [119] [120].

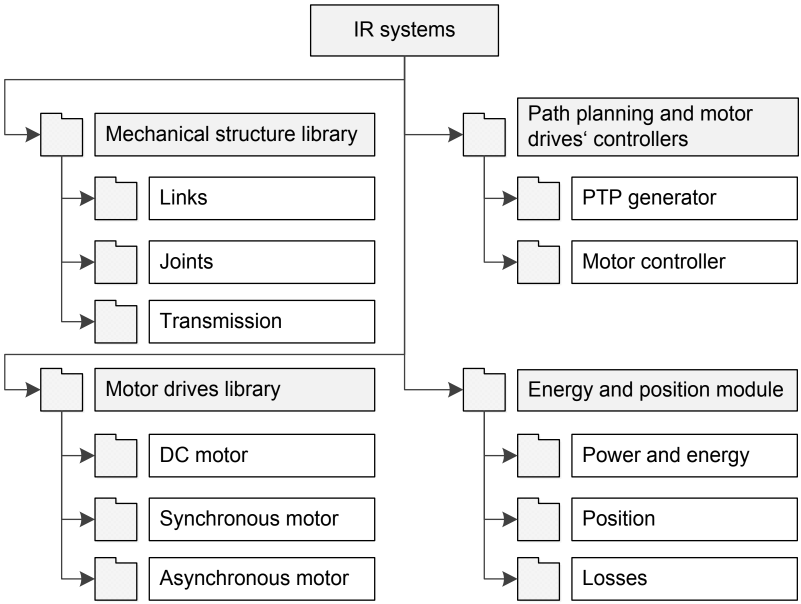

Figure 27: The main components of the IR and their sub-components

In order to develop a model that is able to cope with the modularity, IR's model are divided into several sub-component models. This subdivision can be used to simulate several IR models by choosing the exact parameter to match the specifics of the defined robot. The structure of the developed simulation model is shown in Fig. 27. Here, the IR model is divided into four main components, which are the mechanical structure, actuating motor drive, path planning and energy and position monitoring component. These main components are further divided into several sub-components. For instance, mechanical structure components comprise of the link, joint and transmission libraries that can be used to develop several models of the robot structure, including their 3D CAD representation. Motor drives components comprise of the DC motor, the synchronous and the asynchronous motor library. Besides this, the path-planning and controller library consists of the components that are used to create an instruction for the robot's motion and to control the robot system. The monitoring component model is developed for the purpose of monitoring the energy consumption as well as evaluating the position of the robot.

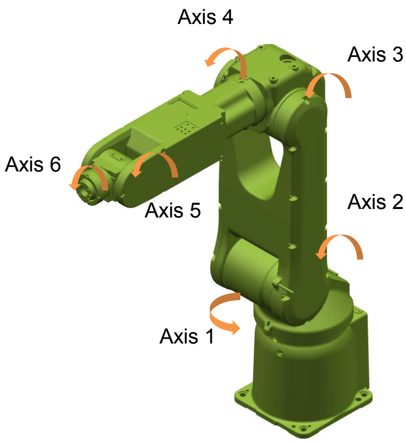

Figure 28: The main structure of the Motoman MH5L [121]

The MH5L is a six axis IR with a maximum payload of 5 kg produced by Motoman, which is commonly used in assembly and HS. The robot is compact with six controlled axes and has a maximum reach of 895 mm with repeatability at 0.03 mm. The robot is 29 kg in weight and requires a power input of 1.0 kVA. The robot can be installed on the floor, from the ceiling or by the wall. [121]

The kinematics model of the investigated robot is shown in Fig. 28, which shows the six axes of rotation and the mechanical structure. The configuration of angles, as shown in Fig. 28 will be referred to as the initial configuration (or home position), which means that all six joint angles are assumed as zero for this setting.

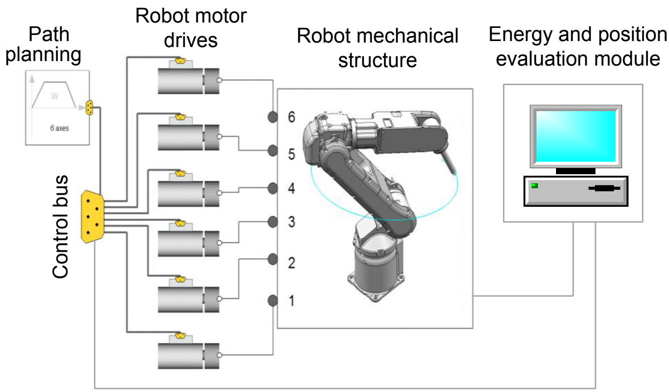

Figure 29: The general model of the robot system

In order to examine the energy consumption, dynamics and kinematics behavior of the robot which is used in the UCM cell, the robot is modeled as shown in Fig. 29. The path planning module yields the fastest direct trajectory (in the configured coordinate space) between a specified start point and target under the given restrictions of using maximum velocity and acceleration. The motor drives actuate the robot's axes via gear transmissions to produce a movement of the robot structure, which contains the information of the robot's inertial and kinematics parameters. Additionally, the energy and position evaluation module is used to evaluate the energy consumption and the position of the robot arms. To be more precise, this module consists of two sub modules, one of which is responsible for power and energy handling, the other for position evaluation. Both extract the necessary information from the control bus in order to obtain information about where energy is consumed, and of the difference between the desired and actual position.

The detailed description of each of the robot's main components and its modeling methodology are presented in Section 4.2, 4.3, 4.4, and 4.5 as follows.

4.2 Simulation model of the robot path planning

Point-to-point (PTP) path planning is used for the IR model. It generates trajectories in configuration coordinate space from one point (q_1) to another point (q_2) based on the input parameters. The motion is generated in a way that all axes involved in the trajectory are not only moving, but also accelerating and deaccelerating. This means, the shapes of the position, the velocity and the acceleration lapse of each angular coordinate are identical. However, they differ in absolute values. The trajectories are generated as the fastest possible motion between start and end positions under defined maximum velocity and acceleration (kinematics constraints). Thus, start and end position, maximum acceleration and velocity have to be defined for every robot axis.

Table 6: The maximum speed and the range of the robot axes of Motoman MH5L [121]

Axes	Range of motion	Maximum speed
Axis-1	±170°	4.71 rad/s (270°/s)
Axis-2	+150° to -65°	4.88 rad/s (280°/s)
Axis-3	+225° to -138°	5.24 rad/s (300°/s)
Axis-4	±190°	7.85 rad/s (450°/s)
Axis-5	±125°	7.85 rad/s (450°/s)
Axis-6	±360°	12.57 rad/s (720°/s)

Data of the input parameters of the PTP path planning, which are range of motion, maximum velocity and acceleration, are taken from the robot's specifications (as shown in Tab. 6). This means that input parameters for the PTP path planning model should not exceed these values. As an example, the profile for velocity and position at the maximum acceleration of 2 rad/s^2 are shown in Fig. 30. For differing conditions, the shape of the position, speed and acceleration profile of each motion-involved axis is in principle the same as the sample trajectory shown in Fig. 30, but with different values for maximum velocities and accelerations.

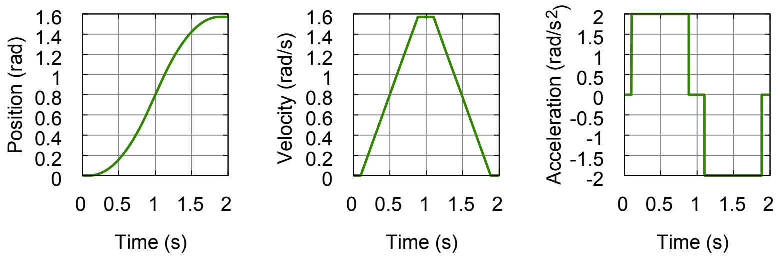

Figure 30: Example of position, velocity and acceleration profile of one coordinate for maximum acceleration a_{max} = 2 rad/s^2 and maximum velocity ω_{max} = 1.571 rad/s [116]

However, the maximum velocity value of the limiting axis might never be reached, resulting in triangular velocity shapes, rather than trapezoidal ones. Using a rectangular acceleration profile makes the velocity and position change instantaneously and results in a trapezoidal or triangular velocity curve. The determination of the applied acceleration and velocity profiles for each axis for multi-axial movement is deduced from [122].

4.3 Simulation model of the robot motor drives

Robot motor drives are the main component of IR that are used to actuate the robot's mechanical structure. The robot motor drives can be synchronous or asynchronous machines, but most six-axes IR employ permanent magnet synchronous motors (PMSM) or induction motors [2] [99]. The standard models of several synchronous and asynchronous motors are developed in the MSL, which can be used in the robot model. However, to keep the dissertation concise, the description of the electrical motor is focused on PMSM since this kind of motor is commonly used for IR drives due to its capability to produce a rapid and an accurate response with fast starts and stops.

There are three main components in the motor drive model, which are the electrical motor (PMSM), electrical motor control systems and motor transmission chain. The general structure of the model is shown in Fig. 31.

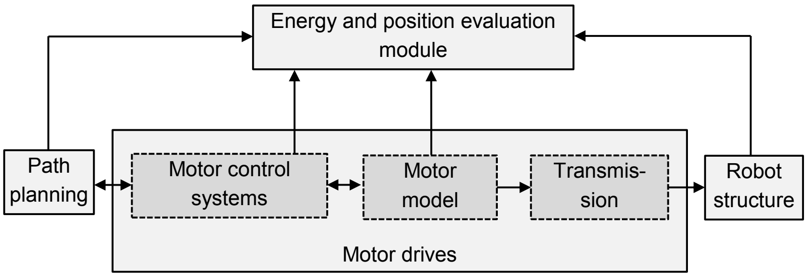

Figure 31: The general structure of the robot motor drives and their connections

The following sub-chapters elaborate on each motor drives component.

4.3.1 Electrical motor

From the point of view of the modeling methodology, the model of PMSM is similar to the brushless direct current machine (BLDC) and brushless alternating current machine (BLAC) because of their identical structures. Therefore, the model of the PMSM can be used for both of these machines. The difference is the way of control, i.e. PMSMs are driven by sinusoidal voltage signals, while BLDC motors are supplied by rectangular signals. [123]

To express the physical behavior of the PMSM, the following parameters are described in the developed model (see Tab. 7).

Table 7: The relevant parameters of PMSMs

Symbol	Meaning
$i_a(t), i_b(t), i_c(t)$	Instantaneous phase currents of the three phases
$U_a(t), U_b(t), U_c(t)$	Instantaneous phase voltage of the three phases
${}^{dq}U(t), {}^{dq}i(t)$	Voltage and current space phasor in *dq*-space
J_{rot}	Moment of rotor inertia
L_m	Stator main field inductance
L_σ	Stator stray inductance
p	Number of pole pairs
R_s	Stator resistance
φ	Power angle

The model of the motors is generated by connections of several sub-models of the electrical components such as resistance, inductance, inertia and air gap, as shown in Fig. 32.

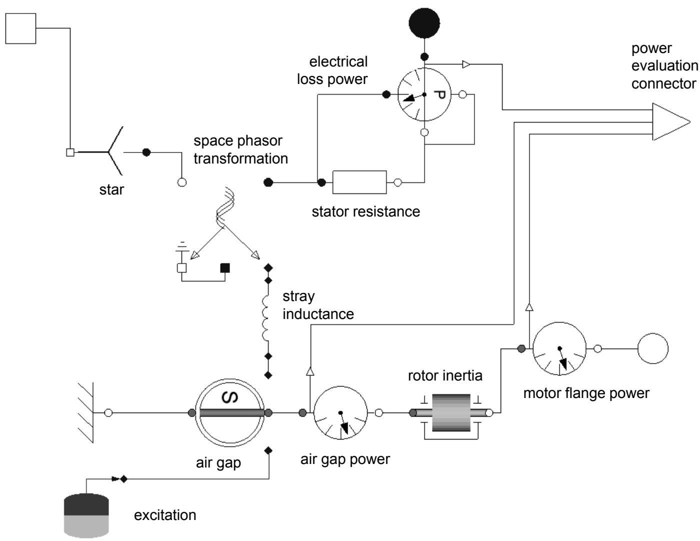

Figure 32: Screenshot of the PMSM model [116]

The electrical supply of the stator windings is modeled by the three phase connector at the top right which consists of three pins, each having a voltage variable as a field quantity and a current variable as a flow quantity. The three windings are connected in a star circuit with a grounded star-point. According to Kirchhoff's first law evaluated at the star point, this results in the following equation:

$$i_a(t) + i_b(t) + i_c(t) = 0 \tag{1}$$

This implies a redundancy of the three phase currents, motivating the transition to the space phasor domain. This transition between phase currents and current space phasors in a stator-fixed coordinate system is accomplished by the matrix equation [123]:

$$\begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \tag{2}$$

Electromagnetic effects are modeled in the space phasor domain, which is present in the stray-inductance component and within the airgap sub-model that is part of the MSL. Furthermore, the airgap sub-model represents the electromechanical connection between current and motor torque. The effective torque at the motor's flange is reduced by the inertia of the rotor, and this effect is taken into account for as well. Altogether, the equations implemented by the model of the PMSM are (in space phasor domain) [124]:

- The current-voltage equations in *dq*-space:

$$\begin{aligned} U_d &= R_s I_d + \left(L_m + L_\sigma\right)\frac{dI_d}{dt} - p\omega_m L_m I_q \\ U_q &= R_s I_q + (L_m + L_\sigma)\frac{dI_q}{dt} + p\omega_m L_m (I_d + I_E) \end{aligned} \tag{3}$$

- The torque equation:

$$\tau_m = \frac{3p}{2} L_m I_E I_q - J_{rot}\dot{\omega}_m \tag{4}$$

- The transformation into the rotor-fixed coordinate system (analogous for voltages):

$$\begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} = \begin{bmatrix} \cos(\varphi) & \sin(\varphi) \\ -\sin(\varphi) & \cos(\varphi) \end{bmatrix} \begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \end{bmatrix} \tag{5}$$

It can be observed that the equations for both U_d and U_q are equivalent to a series connection of the winding resistance R_s, the total inductance $L_m + L_q$ per winding and a cross coupling term dependent on the electrical angular velocity $p\omega_m$, the main field inductance L_m and the total current I_q and $I_d + I_E$ in q-direction and d-direction respectively. In d-direction, the total current not only consists of the d-component of the stator current, but also of the equivalent excitation current I_E. Moreover, the effective torque is a linear function of the cross current I_q. Hence, except for the coupling terms, the behavior of the PMSM is similar to a DC machine.

The evaluation of the motor's input, output, storage and loss power is done by the electrical and mechanical power measurement devices as well as by the motor power evaluation module.

The power flow from the positive to negative pin is assumed to be positive, flowing from flange *a* to flange *b*, respectively. The motor power evaluation module then performs a calculation of the remaining occurring power values with respect to the motor model. Further, these quantities are then fed into a common axial power bus making it available for power evaluation modules downstream.

4.3.2 Control system of the electrical motor

In order to provide an efficient position control, a torque-control has to be established so that the drive delivers the desired torque at its flange at the highest possible accuracy. Since, as pointed out in Eq. 4, the cross-current determines the torque, the current is used as the control variable for the electrical machine.

The basis for the control system is the relationships as established in Eq. 2 to 5. It exploits the mentioned effect of the similarities of the PMSM's equations to a DC machine in *dq*-space. Hence, in *dq*-space, control can be accomplished similar to DC machines, too. In order to achieve this, the incoming measurement values of the three phase currents as well as the target voltage signals are converted to the virtual space-phasor domain. Then, the control of the *q*-current and the *d*-current is carried out. The target value for the *q*-current is calculated from the desired torque, the measured angular acceleration and the characteristic motor parameters by evaluating Eq. 4. Since no field-weakening applies here, the *d*-current is controlled and held at a value of zero.

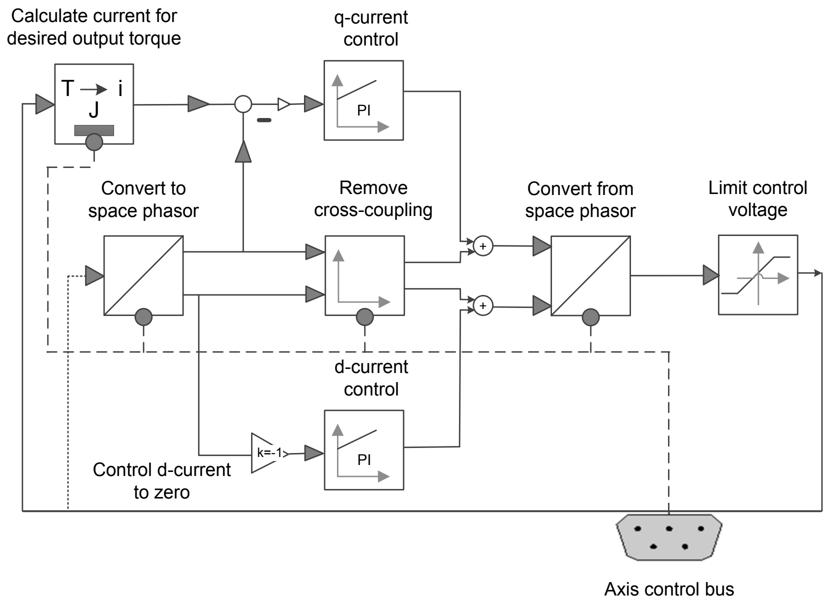

Figure 33: Field-oriented control model of PMSM

The virtual electrical system to be controlled is equivalent to a series connection of resistance and inductance for both the *q* and the *d* branch [124] [125]:

$$U_d = R_s I_d + (L_m + L_\sigma)\frac{dI_d}{dt}$$
$$U_q = R_s I_q + (L_m + L_\sigma)\frac{dI_q}{dt} \tag{6}$$

For design of the control system, the transmission function in Laplace domain is referred to:

$$\frac{I(s)}{U(s)} = \frac{1}{R}\frac{1}{\frac{L}{R}s+1} = \frac{1}{R}\frac{1}{\tau_m s+1} \tag{7}$$

From this equation, we can infer that the electrical characteristics of the current control exhibit first order (PT1)-behavior. By choosing the integrator's time constant of the Proportional-Integral (PI)-control as $\tau_i = \tau_m$, the closed-loop transmission characteristics become:

$$G(s) = \frac{1}{\frac{R\tau_m}{K}s + 1} = \frac{1}{\tau_c s + 1} \tag{8}$$

This reveals that the closed-loop PT1 behavior and the control proportional gain directly influences the time-constant of the closed-loop system: a higher K value will result in a faster control response. The only limitation comes from the constraint of the maximum actuating voltage by the inverter.

The inverter is modeled as an ideal three-phase voltage source. In reality, this would be some kind of pulse inverter driven by space-phasor modulation or pulse width modulation, but from an electromechanical simulation point of view, the assumption of an ideal source is sufficient. Normally, the six inverters of an industrial robot are mounted on a common DC link which allows energy recuperation into the DC link capacitor. This means, with the possibility of energy recovery, negative braking power is not lost, but stored in the DC link capacitor or fed back into the supply grid. Negative input power, hence, can be accounted for and reduces the total energy loss. For cases without energy recovery, negative power must be accounted for as lost power and included into the power balance. Distinguishing between these cases is the task of the evaluation module for lost input power.

As for the trajectory servo control, two approaches can be considered which modern IR follow. On the one hand, feedback linearization or computed-torque controllers (CTC) are used. The computed-torque approach feeds a backward-dynamics model of the robot's mechanical structure to the measured axial angles and angular velocities as well as to the desired acceleration values for each axis. The obtained angular torques are used as the feedforward part of the control system. [118]

In addition to this, a Proportional-Integral-Derivative (PID) state feedback control is employed to compensate for the non-ideal behavior of the model and for disturbance effects. As the deviation between the control model and the actual mechanical system is small, this results in a linear system controlled by the PID state control. This constitutes in effect the main advantage of CTC, which is that linear control theory can be used to tune the PID control, allowing for optimal settings and similar behavior throughout the entire working space. [126] [127]

On the other hand, separate-axes control, which is chosen for this work, is also widely in use. As the name indicates, this approach involves augmenting all the axes with a separate and independent servo control. Compared with the CTC method, this approach takes advantage of a simple control structure. In detail, the control structure consists of a proportional position control and a PI velocity control (as shown in Fig. 34).

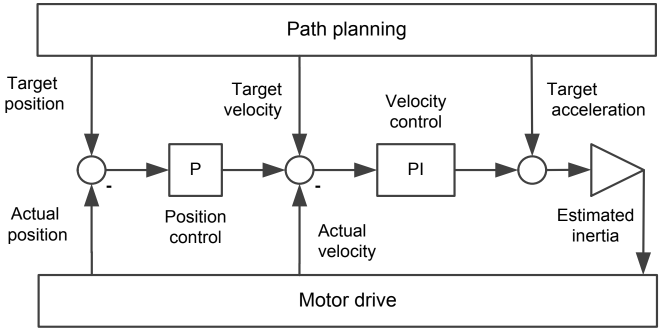

Figure 34: Schematic model of the position control in loop with drive and path-planning

To establish a quick control method, the conventional P-PI feedback controller is improved by two further feedforward parts. Since, in addition to the target position, the target velocity and acceleration are known a priori, their values can be added to the output values of the position control and velocity control. This results in the quick availability of the correct velocity and acceleration values necessary to accurately perform the given trajectory without the control having to adjust to those values. Regardless, the position and velocity feedbacks are employed to compensate for uncertainties of the non-ideal behavior of the model and especially for the deviation of the current configuration from the designed control.

Altogether, the control scheme yields a desired acceleration that is converted to a torque value by means of an estimated value of the inertia. This can take the form of the value of the axial inertia of the controlled drive in a certain robot configuration.

4.3.3 Transmission and drive train

The drive train connects the motor drive shaft to the actuating flange of the revolute joint. There is a gear transmission and bearings between the motor and the driven joint. Moreover, the shafts possess structural damping and elasticity, which are taken into account for, represented as spring and damper elements as shown in Fig. 35.

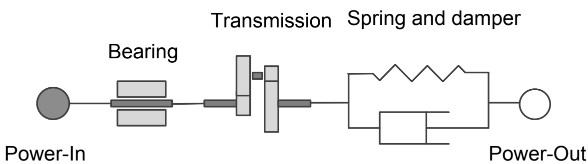

Figure 35: Model of a non-ideal gear drive with friction and damping

The flange model on the left is connected to the motor drive shaft, while the one on the right side is the link to the manipulator arm. For the power evaluation, several power values are taken into account, and are measured by mechanical power evaluation device models. These include the input and output power, the power lost over the bearing element and the power in the form of elastic power stored or released [116].

The maximum values of joint angular velocities can be taken from the MH5L specifications. Furthermore, the gear transmission ratios can be estimated as the ratio between these given maximum angular velocities and the maximum design speed of the motor. This allows for the full exploitation of the operating range of the machines' velocity, entailing the maximum possible torque after gear transmission. The sufficiency of the output torque was counter-checked with the mechanical torque (sum of acceleration torque and gravity balance torque) at its most taxing value, i.e. maximum inertia, for the configuration of each axis.

4.4 Simulation model of the robot mechanical structure

The robot mechanical structure consists of 6 manipulator links and their joints, which are arranged as shown in Fig. 36. In every robot arm model there is a CAD model that represents the three-dimensional appearance of the link, which is used for animation and representation purposes. The input parameters of the arm model such as robot dimension, mass and inertial parameters are gained from the robot specifications, real measurement of the robot platform and from an approximation based on the CAD data. For example, the inertial tensor on the robot arm can be approximated and calculated using CAD software, which is performed based on the geometry of the arm. In this study, Catia V6 was used.

Application of CAD software on the calculation of the inertial tensor of IR can reduce development time and effort, and it is thus commonly used by researchers, such as presented in [128]. Furthermore, a detailed approximation method for determining the inertial tensor of an IR structure can be found in [129].

To permit the extraction of the inertia data from the MH5L's CAD model, every link is assumed as being a rigid body with a homogenous density, which can be obtained by considering the total specified mass m_{tot} = 29 kg and its total volume V_{tot} = 0.01833 m^3 given by the CAD data, resulting in a value of ρ = 1582 kg/m^3. Based on this calculation, the inertial values of the robot are obtained (as shown in Tab. 8).

Table 8: CAD-estimated inertial values of the MH5L

Link	m (kg)	I_{11} (kgm^2)	I_{22} (kgm^2)	I_{33} (kgm^2)	I_{21} (kgm^2)	I_{31} (kgm^2)	I_{32} (kgm^2)
Base	8.797	0.045	0.049	0.043	1.469e-5	4.233e-4	-1.412e-5
1	4.302	0.016	0.024	0.018	-9.707e-5	-0.007	-9.413e-5
2	7.072	0.127	0.103	0.036	-5.056e-5	9.987e-6	0.001
3	3.682	0.010	0.013	0.011	-1.539e-4	-0.001	2.25e-4
4	4.672	0.008	0.042	0.044	-0.001	-8.312e-6	-1.671e-7
5	0.445	2.864e-4	4.947e-4	4.439e-4	2.299e-6	3.07e-7	2.214e-6
6	0.078	1.964e-5	1.702e-5	1.697e-5	5.434e-8	8.29e-10	4.235e-22

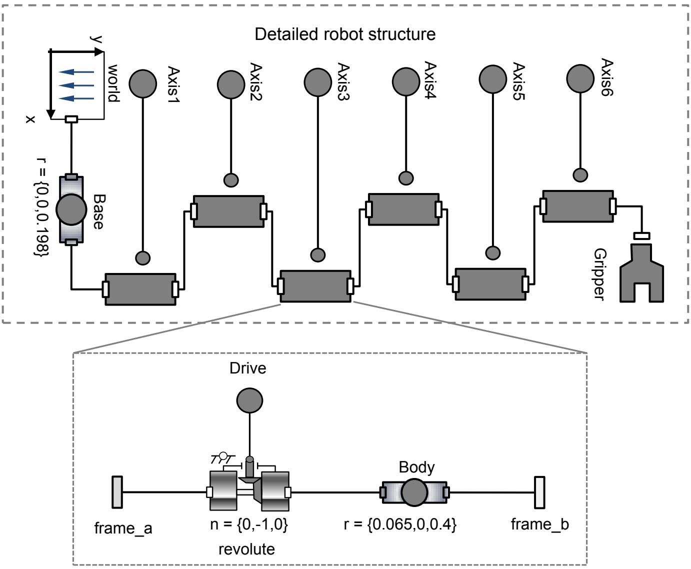

Figure 36: The simulation model of the robot mechanical structure [2]

As shown in Fig. 36, there are connectors (1-6) for the drive train flanges of each axis. Thus, the torque and angular position of each flange are linked to the ones of the appropriate drive. Beside the body models, the entire mechanical model also includes the world frame, the base reference frame of the multibody system and the gripper model.

4.5 Simulation model of the energy and position evaluation module

In order to monitor the energy consumption and the accuracy of the IR, the simulation model of the energy and position evaluation module is embedded within the robot simulation model.

Modeling of the energy evaluation module

The energy evaluation module is used to depict the power flow in every component of the robot. Using these measurement values a preliminary evaluation of local power drops and losses is carried out by distributed power evaluation modules which feed their results into a power evaluation bus. The obtained power values occurring within the electrical drive are:

- electrical input power
- inverter loss power
- stator resistance loss power
- core loss power
- total motor loss power
- inductance stored power
- airgap power
- rotor inertia stored power
- total motor stored power
- mechanical output power

Accordingly, the power values occurring within the drive train are:

- bearing and damping loss power
- total mechanical loss power

Taking these values from the bus, the main power evaluation module calculates firstly the following total power values which cannot be obtained by the distributed power evaluation module:

- total lost power (mechanical losses, motor losses, inverter losses)
- total storage power (elasticity, rotor inertia and inductance stored power)

Then, in a second step, each power data is integrated over time to obtain the corresponding transmitted total energy. Thirdly, to enable the overall evaluation of the whole robot, each energy as well as power component is summed up over the six axes.

By this evaluation module, all the power data is made available in one component (power evaluation bus) for investigation of the effect of the operating conditions and the robot simulation parameters, e.g. speed, friction, damping, control gain, etc. Thus, a detailed power inspection of the whole system of the robot shown in Fig. 37 is possible.

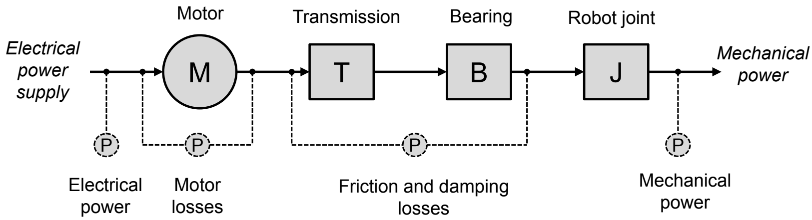

Figure 37: Power evaluation module

Modeling of the position evaluation module

The position evaluation model is designed for tracking and evaluating the actual position of the robot axes. For this purpose, the model compares the input parameters of the path planner that delivers the target path in angular coordinates to the actual position of the joint axes. Both of these values for each axis are available on their control and measurement buses. Then, in order to evaluate the deviation of the six joint coordinates, the desired (target) trajectory is compared to the actual trajectory. The schematic model of the position evaluation module is presented in Fig. 38.

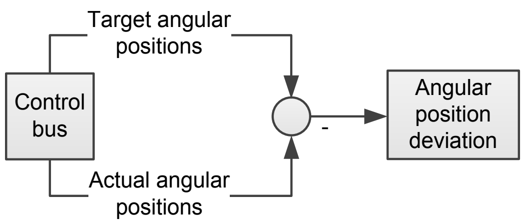

Figure 38: Working principle of the position evaluation model: comparison of actual and reference coordinates

4.6 Power losses model of the industrial robots

In this sub-chapter, the power losses of the IR model are presented. To develop a high accuracy IR model, which is used to evaluate their power and energy consumption, it is important to consider the power losses of IR due to their significant contribution to the result of the energy consumption simulation. These losses can be from both mechanical and electrical sources. In an IR, the power losses can be classified into four main losses: power losses in mechanical structure, in the IR' motor drives, in the IR' control systems and power losses in the IR' supporting components (as shown in Fig. 39).

Main power losses in an IR

Power losses in IR drive control systems, e.g.:

- Inverter losses
- Rectifier losses

Power losses in IR motor drives, e.g.:

- Core losses
- Windage and bearing friction losses
- Stator and rotor losses
- Stray load losses

Power losses in IR mechanical structure, e.g. friction and damping in transmission and bearing

Power losses in IR supporting devices, e.g. losses in CPU, monitor, and control units

Figure 39: The main power losses of a six-axis IR system [2]

Power losses in the IR mechanical structure

In the IR mechanical structure, the power losses can be caused by friction, elasticity and damping. Friction, elasticity and damping of the robot structure occurs in gear transmission, gear bearing and in every revolute joint. These phenomena also occur in the damping component, for example in a spring damper. This can also occur due to the lubrication effect. In this work, the friction effect is modeled based on viscous friction (combined with Coulomb friction) that depends on the speed [130], which is expressed as:

$$v(t) \neq 0 : F_f(t) = -F_v v(t) \tag{9}$$

where v is velocity, F_f is the instantaneous friction force and F_v is the viscous friction force.

The decision to choose the viscous friction model is based on real conditions of the bearing in operation in relatively low speed [131]. On the other hand, the elasticity within the transmission chain from the actuator to the revolute joint is mainly brought about by torsion of non-rigid shafts [132]. The simulation models of these losses are embedded into the bearing and transmission model by defining their friction and damping coefficients, as showed in the Fig. 35.

Power losses in the IR motor drive

The electrical power losses in IR motor drives and their mathematical model are listed in this sub-section. These include core losses (p_c), windage and friction losses (p_f), stator and rotor losses (p_r), as well as stray load losses (p_s). Thus, the model of every motor loss (p_{loss}), can be described as:

$$p_{loss} = p_c + p_f + p_r + p_s \tag{10}$$

For the modeling purpose, the losses model of the IR motor drive are [2] [133] [134]:

Core losses

These losses are also called iron losses, which occur because of the magnetization process of the core material (hysteresis) and by the eddy current effect taking place in that process. Core losses generally contribute to about 20-25% of the total motor losses. Mathematical equations that are used as the basis for the development of Modelica® models are expressed as follows:

$$p_c = p_{ref}(r_H \frac{\omega_{ref}}{\omega} + 1 - r_H)(\frac{v}{v_{ref}})^2 \tag{11}$$

The core losses are modeled based on the velocity of angular remagnetization (ω), actual voltage (v) and hysteresis ratio (r_H). Therefore, p_c can be modeled as a frequency-dependent conductor that is expressed as:

$$G = \frac{p_{ref}}{v_{ref}^2}(r_H \frac{\omega_{ref}}{\omega} + 1 - r_H) \tag{12}$$

In the first implementation, the ratio of hysteresis losses is defined as r_H = 0. The reason for this is that the velocity of the changes in the magnetic field is difficult to model in Modelica® since the language cannot easily express this condition. In this research, the r_H is modeled only at value 0, 0.25, 0.5, 0.75, 1, depending on the value of the angular velocity, which is also suggested by [134].

Stator windage and friction losses

These kinds of losses are mainly caused by the air resistance of the motor and the bearing friction and losses. In motor drives, these losses contribute to around 8-12% of the total motor’s losses. These resistances are relatively constant at several motor loads, but the amount of the losses does depend on the motor speed. In the Modelica® model, these losses are modeled based on the following equations:

$$\tau = sign(\omega)\frac{p_{ref}}{\omega_{ref}}\left|\frac{\omega}{\omega_{ref}}\right|^{power_{\omega}^{-1}};$$

$$For\ -\omega_{Linear} \le \omega \le +\omega_{Linear}: \tag{13}$$

$$\tau = \frac{p_{ref}}{\omega_{ref}}\left(\frac{\omega_{Linear}}{\omega_{ref}}\right)^{power_{\omega}^{-1}}\left(\frac{\omega}{\omega_{Linear}}\right)$$

In these equations, the exponent power (ω) is set to 1.5 for axial ventilation; while for radial ventilation it is set to 2 [134]. Furthermore, to have a stable simulation model, the friction torque is modeled by a linear curve.

Stator and rotor losses

These kinds of losses are caused by the current that flows though the stator winding and the rotor. In other terms, stator and rotor losses are also known as I^2R losses. The main effect from these losses is the production of heat at the rotor and stator. Around 55-60% of the total motor's losses are attributed to I^2R losses, depending on the motor load. In the Modelica® model, the stator and rotor losses (p_r) are expressed as shown in Eq. 14:

$$p_r = i^2 R_{Operation};$$

$$R_{Operation} = R_{ref}\left(1+\alpha_{ref}\left(T_{Operation}-T_{ref}\right)\right); \tag{14}$$

$$\alpha_{ref} = \frac{\alpha_{20^\circ C}}{1+\alpha_{20^\circ C}\left(T_{ref}-293.15\right)}$$

Where, p_r is the stator and rotor losses, i is the current, R is the resistance, α_{ref} is the temperature coefficient of the used material and T_{ref} is the reference temperature.

Stray load losses

This loss occurs as a result of the leakage fluxes through the winding of the stator. It accounts for about 4-5% of total motor losses, depending on the motor load capability. Based on the standards EN 60034-2 and IEEE 112, this lost is modeled based on the following equations:

$$p_s = \tau\omega;$$

$$\tau = \frac{p_{ref}}{\omega_{ref}}\left(\frac{i}{I_{ref}}\right)^2\left(\frac{\omega}{\omega_{ref}}\right)^{power_\omega - 1} \tag{15}$$

Where, p_s is the stray load losses, ω is the angular velocity of the motor and i is the current of the motor. In Eq. 15, the exponent of $power_\omega$ represents the dependency of the stray load torque on the angular velocity of the motor.

The evaluation of the power model at several motor speeds is shown in Fig. 40, which depicts the comparison of simulation and measurement results [2] [134]. In this figure, the comparison is conducted with an asynchronous induction machine.

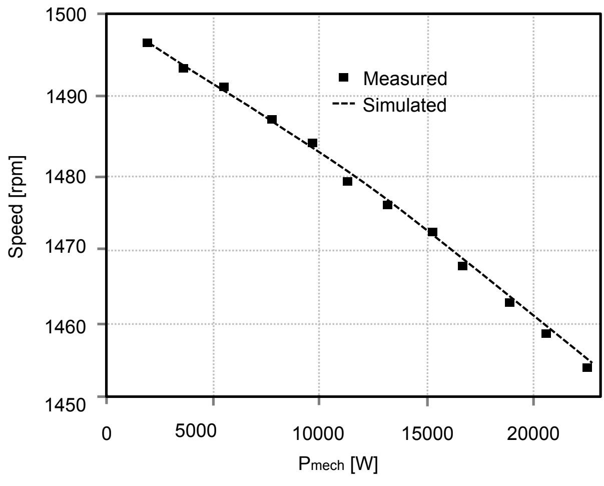

Figure 40: The comparison between simulation and measurement results [134]

Power losses in IR motor control systems

In the control system unit of the robot, there are losses that also occur, e.g. inverter losses. This kind of loss is mainly caused by the rectifier that has the main function of converting the AC power source to a DC source.

Furthermore, losses also occur in the robot supporting components, such as computers, the monitor, and the robot panel. All of these components also require a power source to operate. Since the power consumption of these components is relatively constant, these are not included in the developed simulation model. Based on the measurement result, the energy consumption of these components is about 220W.

To summarize, Fig. 41 depicts the power diagram of energy consumption of an IR together with its losses. From this figure shows that there are many losses occur in an industrial robot. Modeling all of these losses will lead to a high accuracy of industrial robots' simulation model.

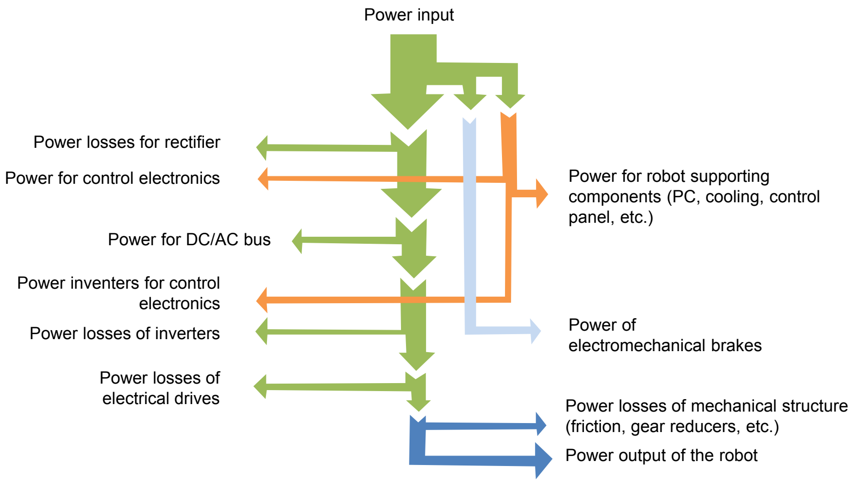

Figure 41: The power demand and losses of an IR (based on [99])

4.7 Summary

An IR model that can be used to simulate its energy consumption, kinematics as well as dynamics behavior will help planning engineers to optimize the IR's operating conditions. By doing so, the energy consumption of an automated HS can be reduced substantially, since most of this system consists of IR as the main components. Therefore, an accurate and modular IR simulation model is desired.

This chapter presents the description and the methodology for the development of a modular IR model that is used for process planning of HS. This includes the description of the IR as a whole mechatronic system along with its main components. The Motoman MH5L robot is used as a case study in this chapter. This IR is used as the handling machine for UCM cells for electronic components inspection. In comparison with other modeling approaches, this work focuses more on the modeling of the IR' internal components, which in common IR modeling methods are simplified or even neglected.

For the purpose of modeling, the robot is divided into four main components, i.e. mechanical structure, motor drive, control systems and energy & position measurement module. The mechanical structure is equipped with 3D CAD for kinematics and work space analysis. The motor drive of the robot is developed based on the PMSM structure, since it is commonly used in the IR industry. However, in this research, several other motor models were also developed and used, both from the modification of the MSL and the author's version. The control system of the IR is modeled using single axis position controllers; while to create the robot movement, a PTP planner is used. Besides these main components, the energy evaluation module is created for visualizing the energy consumption and the power losses of the robot, and the position evaluation module is used to monitor the position of the robot arm. Further, this chapter presents power losses of an IR and how the author involves these losses into the IR model.

To cope with the modularity requirement mentioned previously, several robot models are also developed and examined, for example the ABB IRB 6620 [116]. This modularity was possible by developing the standard component models of IR. Thus, it can be used for other IR models by changing the robot parameters, such as the dimensions, the 3D model and motor specifications. However, the modular model also has a limitation in its model accuracy, due to the limited data that can be obtained from the IR' manufacturers. To solve this issue, verification and validation of the model is needed. Therefore, the validation methodology to check and improve the model accuracy is described in the next chapter.

5. Verification and Validation of the Simulation Model

The main issue in order to use the modeling and simulation approach is how to validate the results. This is because most modeling requires the use of assumptions and approximations. Thus, a verification and validation of the simulation models and their results is suggested in almost every engineering simulation work to ensure that the digital models are an accurate representation of the real system under study. In this chapter, a verification and validation method for analyzing and improving the simulation model of the IR is presented.

This chapter begins with descriptions of verification and validation methods that can be used to check and improve the simulation model. Furthermore, the chapter presents the detailed verification of the six-axis IR model, which includes verification of the equation's consistency and the verification results. An experimental investigation to validate the simulation results is presented in Section 5.3. This section also describes experimental methodology and the experiment results. Finally, some concluding remarks are presented at the end of the chapter.

5.1 Verification and validation methods

Verification is a process of evaluating and determining whether the developed simulation models comply with requirements and specification conditions defined by the developer. Thus, this process is often an internal evaluation, with the purpose of identifying and removing errors in simulation models; whereas validation is a process of evaluating and determining whether the developed simulation models are accurate representations of the actual system's behavior and conditions. Thus, the validation process is a prerequisite for external users. Validation in the form of an experiment is a method that is commonly used for this purpose. Indeed, both verification and validation are facilitating methodologies in the development of simulation models, in order to ensure their quality and accuracy. The simulation models can only be useful as a representation of real systems when their behavior and properties are accurate. Inaccurate simulation models will give wrong simulation results and lead to an inaccurate analysis. Therefore, the verification and validation of the simulation model both have an important role in the simulation analysis. [135]

However, system complexities and limited resources (e.g. time, measurement tools and budget) become issues for the verification and validation processes. Therefore, throughout most of the development process of a complex system simulation model, validation cannot be conducted for all possible scenarios. For example, the validation of the IR model can only be done for its kinematics and energy behavior in specific operating conditions.

Based on [108], the following techniques are common methods that can be used to verify and validate simulation models:

1. review assumptions and approximations that are used in a simulation model,
2. perform sensitivity analysis of the simulation model,
3. perform internal consistency checking of the simulation model,
4. perform a comparison study of the simulation results with the analytical solution,
5. experimental validation, i.e. comparing the simulation and experimental results.

The first three aforementioned methods are used for verification, while the others are for validating the simulation models.

Assumptions and approximations in the development of the simulation model cannot be avoided. Thus, checking the assumptions and approximations made for every IR component model is mandatory. The review can be done by measuring and analyzing the actual component of the IR. Another verification method, called sensitivity analysis, is used to improve the understanding of the relationship between input and output parameters in the simulation model. For example, the sensitivity analysis of the motor drive is performed by analyzing the effect of the voltage and currents input to the speed and torque. Since the IR component's model is created using Modelica® language, the verification can also be done by checking the mathematical equations behind the model, as well as checking the equation for consistency. In the Modelica® simulation software, there is a tool that can be used to check the mathematical equations and their consistency. This is done by balancing the number of variables and equations of the model.

The validation method for simulation results is performed by comparison with another analysis approach, e.g. by comparison with analytical or experimental results. However, the comparison study cannot prove that a simulation model is accurate for all possible conditions. Rather, it merely proves that the simulation model is accurate from a design perspective. Due to the limitation of the analytical solution, the analytical validation is limited to a simple model of the IR' components. Thus, the best validation method is by experimental validation.

In 1979, the Society for Computer Simulation (SCS) [136] developed a diagram that described a general method for developing a computer simulation model (as shown in Fig. 42). This diagram shows a basic scheme of simulation model development (solid lines), which includes verification and validation activities (dashed lines).

Reality in Fig. 42 represents the actual systems under study. It can be the physical system in its entirety or in part. In the development of the IR' simulation model, *reality* is the IR as a whole system or its components. Moreover, *reality* also represents a specific problem being investigated, e.g. energy, dynamics, control, or kinematics problems.

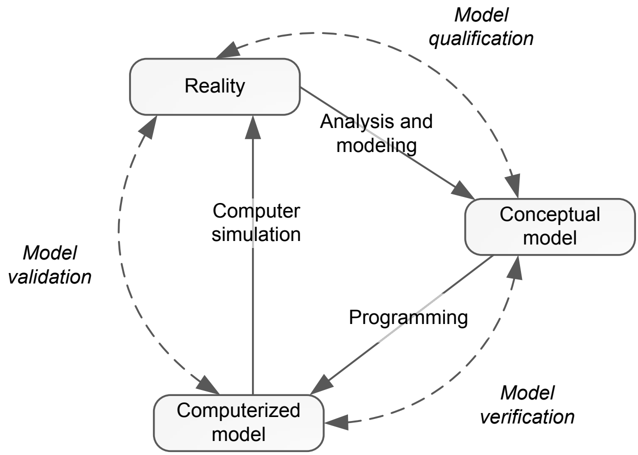

Figure 42: The verification and validation cycle in the development of a simulation model [136]

The *conceptual model* represents the mathematical equations that describe the physical reality. In Modelica® language, the conceptual model is described by differential, algebraic and discrete equations. The conceptual model also includes the description of the initial and boundary conditions of the systems. After that, the conceptual model is used to develop the computer model, which comes usually in the form of a solution algorithm with numerical approximation and convergence criteria [135]. Using the computer model, an experiment on a computer can be performed in order to analyze the behavior of the real systems.

The process of extracting the data from actual systems and describing them in mathematical equations is called analyzing and modeling, while the reviewing process is called model qualification. This step includes ensuring the theories and assumptions that were used in the mathematical concept model are correct. The conceptual model should represent the entity of the real system. After that, the verification and validation task has the function of improving and checking the accuracy of the developed model. Detailed verification and validation procedures and their results are described in the following Sections 5.2 and 5.3.

5.2 Verification of the six-axis industrial robot model

Fig. 42 presents a flowchart indicating the activities involved in model development in general, without detailed descriptions of the processes. To describe verification and validation processes more specifically, an extended diagram is created (Fig. 43). The figure shows in greater detail the workflow in the development of the IR simulation model together with the verification and validation processes. The verification is done in order to ensure that the mathematical models are implemented correctly in the computer models. Validation is performed via experimental investigation in order to compare and predict the accuracy of the simulation results.

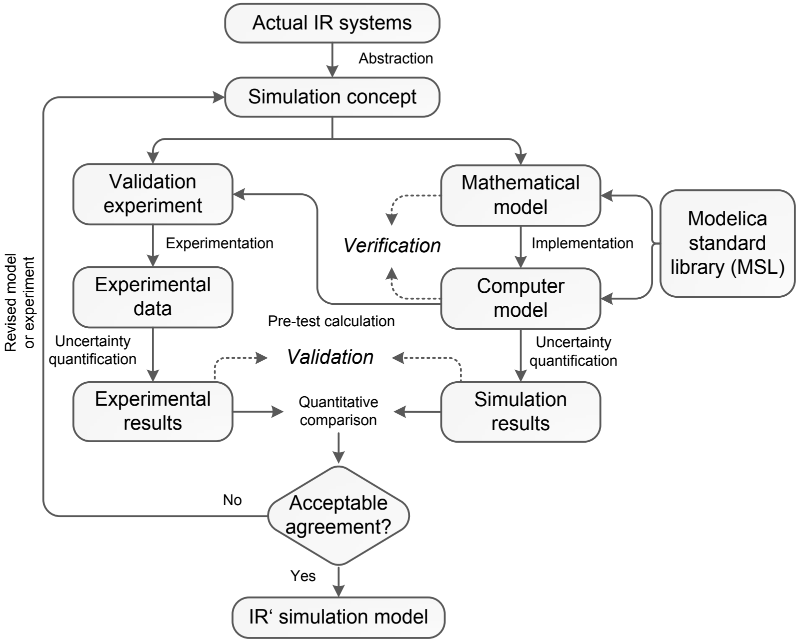

Figure 43: The model development, verification and validation process of the IR model

As explained in Section 3.2.4, the IR robot models are developed by a combination of the top-down and bottom-up method. The development process is started with the investigation of the actual robot systems. After that, the simulation concept is defined. This concept includes the verification and validation process. Verification is done by checking the mathematical equations and their consistency, while the validation is performed by an experimental investigation (as shown in Fig. 43).

In the verification of the simulation model, the most important step is ensuring that there are no errors in the Modelica® equations and ensuring the model modularity by following the object-oriented modeling technique. The verification activity is divided into two main tasks, i.e. code verification and mathematical verification (Tab. 9).

Table 9: Classification and focus in the verification of the IR simulation model

Activity	Focus
Code verification	Software quality assurance: reliability and robustness
Mathematical verification	Removing mathematical error from the given equations

Code verification is used to ensure that the software is able to model and simulate the IR for the dynamics and energy behavior analysis. The focus of this activity is to identify programing errors within the software's numerical algorithm. This also tests the reliability and robustness of the software. The quality of the software is checked by developing basic components of IR such as a simple DC motor and analyzing the results. Moreover, code verification is also accomplished via comparison study with the analytical solution and with other similar simulation software such as MATLAB Simulink®. The code verification result from this investigation shows that Catia Systems Engineering is robust and reliable to be used for mechatronic simulation.

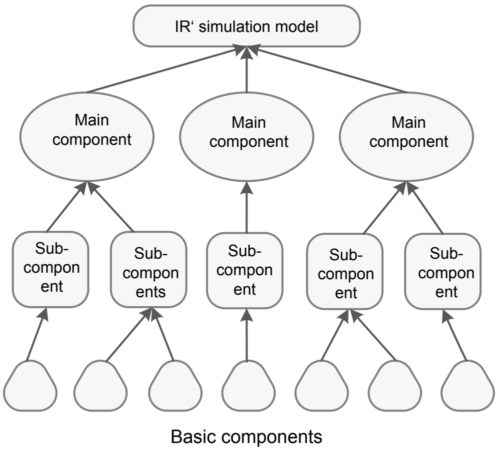

Figure 44: The verification step: from basic components to the entire IR system

Mathematical verification is used to remove errors from the mathematical equations of the IR model. In this activity, the mathematical equations are verified using Modelica® checker, which has the capability to calculate with the given variables and parameters in the set of mathematical equations. To ensure that the verification process runs efficiently, the process is allowed to run beginning from basic components of the IR model to more complex components, until the whole IR simulation model (as shown in Fig. 44) has been verified. At the end of this verification process, all of the IR component's models should correspond to the pre-defined requirements.

In addition, the verification is also performed informally, according to the author's knowledge. This includes analyzing the IR's real system behavior and its components, and interpreting this based on previous knowledge acquisition and experience of the author.

5.3 Experimental validation of the six-axis industrial robot model

As shown in Fig. 43, the experiment results are used for quantitative comparison in order to define and predict the accuracy of the simulation model. In this section, the experimental investigation for validating the developed simulation model is described. This includes description of the equipment and the experimental method, as well as validation results and subsequent discussion.

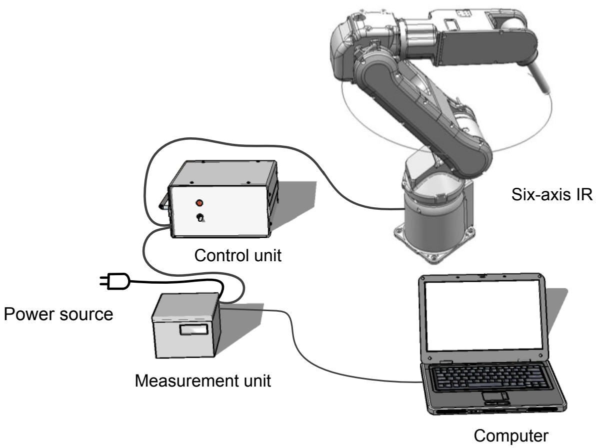

Figure 45: Experimental setup for measuring the electrical behavior of the IR [10]

5.3.1 Equipment and method

The equipment and experimental setup is sketched in Fig. 45, using the energy measuring unit as the main measurement tool. The measuring unit has the ability to measure the electrical data of the robot, e.g. current, voltage and power, at specific operating conditions, during the robot's operation. During the measurement process, the data is automatically stored into the measurement unit's PC and is accessible via internal network.

To validate the simulation results, the experiment is performed under several operating conditions with different payloads and robot speeds. For this experiment, the robot speed is measured at 20% and 40% of the robot's maximum speed and the payload of 2 kg and 3 kg is used. There are three main reasons in choosing these conditions:

- the UCM cell condition, which operates in a narrow working area, inhibits the operation of the robot at high speeds,
- limitation of the robot payload (maximum capacity is 5 kg),
- in accordance with the research purpose, that is to use the simulation model for optimizing the operating condition of the IR, the experimental investigation is only used for the purpose of validation.

All in all, these experimental conditions are sufficient to validate the simulation results. Like almost all other experimental validations, it is impossible to perform investigations for all possible conditions, due to the effectivity and efficiency of doing so.

For a quantitative comparison, the dynamics characteristic and execution time of the IR are used as the criteria for choosing the robot movement. The comparative study is analyzed based on the robot movement from position D to A (see Fig. 26), i.e. q_1 {-167.068, -36.480, -45.378, 4.730, -53.835, 42.986} to q_2 {178.616, -91.097, -45.461, 4.715,-53.874, 43.011}. In this motion, only robot axis 1 and axis 2 are moving, while the other axes are held on the standby position. Using this simulation condition, the difference of the energy consumption behavior both of the axes is easily to be analyzed.

5.3.2 Results and discussion

In order to predict and define the accuracy of the simulation results, the developed robot model is also simulated under the same operating conditions with the experimental investigation. Thus, the data gained from both of these investigations can be used for comparison studies. By using the simulation method, mechanical and electrical data are obtained, such as the current, voltage, power, energy consumption as well as torque and acceleration of every robot axis. Then, the energy consumption is calculated using the electrical data. Meaning, the experimental investigation provides data on the current, voltage and power of the robot during motion. Therefore, drawing from these two methods, comparison of the current, power and energy consumption is conducted.

The quantitative comparison between experiment and simulation results is depicted in Fig. 46, which shows the value of energy consumption and power of the robot. Further, the figure shows that the difference between the simulated result and experimental measurement for power and current is about 5%. Based on the investigation, the factors that lead to this deviation are the robot control unit, mechanical losses of the robot and the robot operating conditions.

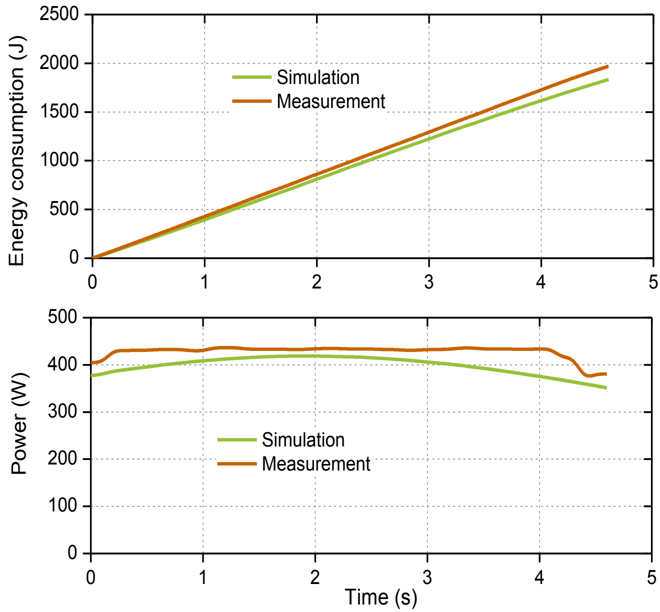

Figure 46: Energy and power consumption of the robot (maximum speed: 20%, payload: 3 kg)

The first factor causing the deviation is the limitation of the simulation tool to model the power losses of IR's support units. Thus in this study, these components are not included in the simulation model. The energy consumption value is gained based on the measurement investigation, which consumes about 220 Watts [2] [137] [138]. A second factor is the operating environment of the robot itself, such as the air temperature and humidity. These factors influence the characteristic of the motor drive, such as its resistance and current.

Although there is a difference between the values of the experiment and simulated results, the power and current trends are very similar. The value of the deviation is also within the defined acceptance criteria, which is set at 7%. Another comparison study, which is conducted by comparing the value of the motor current, at 20% of the maximum speed, is depicted in Fig. 47. This figure shows that the deviation is constant not only for the 2 kg payload but also for the 3 kg payload. The deviation of the current value is relatively minimal, about 2-5%.

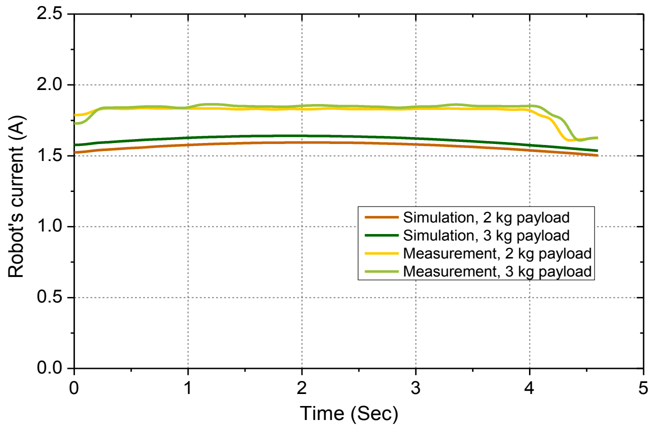

Figure 47: Current of the robot at 20% of maximum speed

The validation result of a more complex robot movement, which all of the robot axis are moved, is depicted in Fig. 48. In this validation, the robot moves for it first 15s. Similar to the previous results, the trend of the power profile both from simulation and experiment's results are same. The deviation is also about 2-5%. Therefore, based on these results it can be concluded that the developed model is accurate enough for predicting the energy and power consumption of the IR.

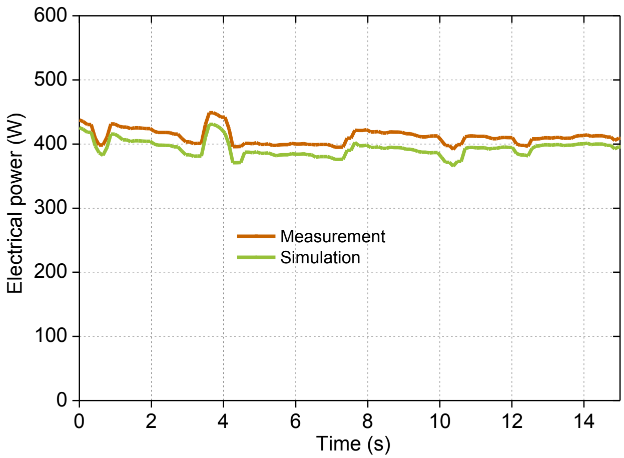

Figure 48: Power consumption of the robot (maximum speed: 20%, payload: 3 kg)

Furthermore, from the simulation results also found that the power losses of the robot contribute about 5%, which is mainly caused by mechanical power losses (3.4%). The comprehensive discussion of the robot power losses is published by the author in [139].

5.4 Summary

This chapter presents the verification and validation activities, which are part of the development process of the IR simulation model. Both these activities have the purpose of ensuring that the developed model is accurate and represents the real IR system. The verification activity focuses on the internal components of the simulation process, e.g. the integrity of the mathematical and simulation code and their accuracy; while the validation activity is done by using experimental investigation to define the accuracy of the developed model.

The verification and validation process is performed based on the standard procedure that was developed by SCS, as shown in Fig. 42 and 43. However, due to limited experiment time and for efficiency, a verification and validation process is designed for a specific operation condition of the IR, which is also commonly employed in the verification and validation process. This means that the collected data for validation is only based on these specific conditions. Therefore, the simulation model cannot prove its accuracy for all possible operation conditions. However, it can provide the evidence that the models are accurate for the purpose of process planning, especially for energy examination.

The deviation between the simulated and experimental results is between 2-5%; this value is relatively low and within the defined acceptance criteria, which is set at a maximum of 7%. Based on the analysis, the deviation is caused by several factors, such as the limitation of the software tool for modeling the robot's operating conditions.

6. Kinematics and Dynamics Analyses of the Industrial Robot

This chapter presents the kinematics and dynamics behavior analyses of the IR. These behavior analyses are important as they provide information on the performance of the robot with regards to its accuracy, precision and motion behavior. In the process planning of IR, the detailed analyses of the IR's kinematics and dynamics behavior is used to form the basis for optimizing the operating conditions of the robot. Furthermore, these behaviors have a strong correlation with the energy consumption of IR since the mechanical energy is a function of robot torque and angular velocity, which are among the kinematics and dynamics parameters.

This chapter starts with the brief description of the definition, scope and current solution methods for the IR kinematics and dynamics analyses. The next section will focus on the kinematics analysis of the IR, which is conducted by using collected simulation data from the developed simulation model. Next, dynamics analysis, which includes robot torque analysis, robot accuracy analysis and the robot speed response analysis, is described. Finally, at the end of the chapter, a summary and concluding remarks are presented.

6.1 Kinematics and dynamics analyses of handling machines

In kinematics analysis, the motion behavior of the machines, such as position, velocity and acceleration, are studied without regarding the cause that sets the body in motion itself. While in dynamics analysis, all these motion behaviors are studied with regards for the cause, such as force and torque, as well as their effect on the body's motion. Thus, a dynamics analysis is more complex than a kinematics analysis. However, every analysis comes with its own advantages. Among these, kinematics analysis provides the best method for the purpose of visualization, while dynamics analysis is mostly used for optimizing the control system of the machines. In the optimization of the IR' operating parameters, both kinematics and dynamics analyses are important since they provide a full picture of the performance of IR, providing information on their accuracy, repeatability and motion behavior.

In HS, a kinematics simulation is used for the work space or layout design, collision detection and for preparing a video presentation, since it deals with the 3D representation of handling machines and their processes. The 3D representations are gained from the CAD data that is integrated in kinematics simulation tools. There are many software tools that can be used for handling process simulation, e.g. Delmia DPM from Dassault Systèmes, Tecnomatix from Siemens PLM and 3DCreate from Visual Components. Furthermore, human simulation models are generally integrated in these software tools, which allows for an ergonomic analysis of human activity.

In process planning of HS, there are many advantages that can be gained using kinematics analysis, which include the possibility of evaluating motion to avoid interference and for planning of the working space. Specifically, the application of kinematics simulations support the planning for a HS in the following ways [140]:

- for performing a spatial analysis of the HS's workcells in order to help engineers develop workable designs,
- for digital mock-up, for viewing the realistic animations of the system for ergonomics analysis and for checking the potential problems that may occur in the handling process, e.g. the possibility of collision of moving parts or poor accuracy,
- for creating animations of process sequences to improve the efficiency of HS as well as for making a video presentation for customers or clients about how the systems will work.

In several kinematics simulation software tools, a kinematics simulation is featured with a FEA analysis that has the ability to analyze motion studies and distribution and deflection of structure stresses. Through this, it predicts potential collision caused by the load and force of the machine structures more precisely. The MSC Visual Nastran is exemplary software that provides this integration. Besides this, research on web-based kinematics in order to cope with the planning issues related to geographical constraints is undergoing, e.g. in [37] [141]. The motion analysis of the systems is performed via the internet. This means that the evaluation of the handling sequence or the systems performance can be accomplished by several planners located in different cities or even countries simultaneously without a physical meeting taking place.

On the other hand, dynamics behavior analysis is mostly used for improving the performance of HS machines. For instance, it is used to improve the IR's performance by adjusting the control parameters, through investigation of the operating conditions, such as payload, speed and acceleration. Therefore, the position, orientation and vibration of the end-effector can be analyzed. Then, this allows the accuracy and repeatability of the robot to be optimized.

Furthermore, dynamics analysis can also be used in the development phase of the IR. However, this advantage is limited to robot manufacturers, which have direct access to the design of the robot hardware and the software system.

In short, the general picture of the functionality and advantages of the kinematics and dynamics analyses for handling machines are depicted here in Fig. 49.

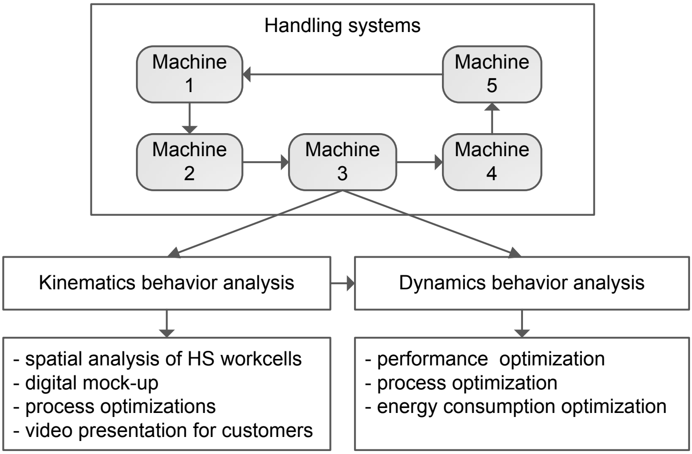

Figure 49: The functionality of kinematics and dynamics behavior analyses in the UCM cell

6.2 Kinematics of the industrial robot: Analysis and discussion

In the kinematics analysis, the kinematics chains of every robot link is studied, which includes the position, orientation, velocity and acceleration of each link. There are two analytical methods to describe kinematics parameters of an IR, which are forward and inverse kinematics. Forward kinematics computes the position and orientation of the end-effector relative to the joint parameters. Conversely, inverse kinematics computes the joint parameters beginning from the position and orientation of the end-effector. In forward kinematics, Denavit-Hartenberg (DH) notation [142] is commonly used which sets rules on how the base coordinate system of every joint is to be set and orientated. The base systems, which are defined as being fixed to the corresponding volume of the link, then allow the orientation of the whole robot to be described in its entirety at every point in time.

However, these methods are over complicated and are not so relevant for the purposes of planning engineers since the methods are primarily focused on the design of IR. Instead, planning engineers are focused mainly on the application of IR in HS. For this reason, a kinematics analysis of handling machines is usually performed by using simulation approaches. In the process planning of IR, the simulation approach offers several advantages, such as collision detection and end-effector position analysis without the need of a detailed mathematical description and experimental investigation. That is why, for planning engineers, the approach is more convenient than the analytical approach.

Based on the developed simulation model that was presented in Chapter 4, the kinematics behavior analysis of the robot is investigated. In this research, the kinematics analysis of the robot as part of the UCM cell includes working space requirement analysis, collision detection and handling process sequence analysis. These aforementioned analyses are described as follows.

6.2.1 Layout analysis and collision detection

The developed Modelica® model is integrated with the CAD software package from Catia V6. Therefore, it can simulate the motion of the robot at several operating conditions. CATIA V6 Systems Engineering enables the implementation of logical models written in Modelica® language in a RFLP-Editor. Thus, adding CAD data with their physical parameters to the Modelica® model can be done easily. As a result it is possible to create a visual simulation of the robot. As follows, based on these simulation results, a planning engineer is able to analyze the layout requirements in order to develop an efficient and effective work place.

Using this model, the dimension, robot working area and the position of every axis of the robot can be monitored. Therefore, any collision that may occur between the robot axis and its tooling systems can be detected. This analysis is very important as the basis for the process planning of IR, especially when the robot operates at high speeds and in a narrow working space.

For example, several motions of the MH5L robot operating in the UCM cell are shown in Fig. 50. Like other kinematics simulations, the motion of the robot can be analyzed in detail, e.g. by zooming, slow motion, and rotation. Thus the detailed motion of every robot axis can be well monitored in order to check the possibility of a collision and to ensure that the robot operates smoothly in the allocated working space.

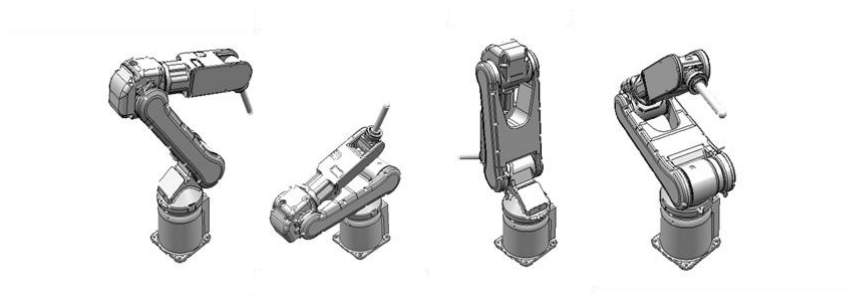

Figure 50: Several robot positions during its operation

Since an efficient layout is an important parameter in the development of an efficient HS, it can be optimized via a reduction of the required working space. The motion analysis of the robot, as visualized on the computer screen, can be used for this purpose. This reduces the capital cost that is used for developing a HS. The kinematics motion also provides spatial information of the robot working space, which is useful for process planning of the handling process.

Furthermore, the motion of the robot that is used in the UCM can detect inefficiencies or malfunctioning of the systems. The analysis is performed to calculate the distance, velocity and acceleration during operation. The data is then used as the basis for improving the performance of the handling process, e.g. for optimizing the operating speed of the robot.

To get a general overview of the strengths and weaknesses of the mechatronic simulation approach for analyzing the kinematics and dynamics behavior of handling machines, a comparison study of several simulation approaches is presented in Tab. 10.

Table 10: The advantages of the mechatronic simulation approach compared with existing common simulation approaches (circle with full grey means very superior and circle with white color means cannot be used)

Type of problem	**Kinematics simulation**	**FEA simulation**	**Dynamics simulation**	**Mechatronic simulation**
Layout analysis	●	○	○	◔
Collision detection	◕	●	◔	◑
Mechanism analysis	●	◔	◔	●
Deformation and stress-strain analysis	◔	●	○	○
Sequence analysis	●	○	◔	◕
Vibration analysis	○	◑	●	●
Control systems analysis	○	○	●	●
Accuracy analysis	○	◑	●	●

Based on Tab. 10, the mechatronic simulation approach works well for dynamics behavior analysis but is weaker than other simulation approaches for kinematics behavior analysis. However, this is sufficient for analyzing the kinematics behavior of a single handling machine. This limitation is more obvious when visualizing several handling machines in one simulation environment. Therefore, collision detection is restricted only to collision among the robot components.

By using the mechatronic simulation approach, the collision detection among the IR's components is detected by analyzing the position and motion of the robot's arm. Collisions occur when any intersections between the parts of the robot CAD model are found. In the UCM cell, where the robot must perform many operations to place the PCB through tight positions, the mechatronic simulation is used to ensure the motion of the robot is within the given tolerance zone and is free from collision with the robot structure.

6.2.2 Process sequence optimization

Process sequence is one of the subtasks of process planning that aims to specify the sequence of the machine motion and handling process. Many constraints are taken into consideration for this task, including geometrical constraints, technological constraints and economical constraints [143]. Examples of geometrical constraints are dimensions, shapes and features of the HS, while technological constraints are parameters that belong to the machine, such as machine vibration, accuracy and deformations. Economical constraints then include the cost of the HS process and its efficiency.

The efficiency of an automated HS equipped with IR depends on the robot's sequencing moves. In particular, HS that are equipped with only a single robot, such as the UCM cell, are very affected by the robot motion in regards to the handling times, process effectivity and efficiency [144]. Thus, a well-planned robot process sequence is required in order to reduce the operating time and energy consumption of HS. Therefore, an efficient approach is needed for process sequence optimization. The mechatronic simulation approach can be used to solve this issue, i.e. for optimizing the process sequence of the robot.

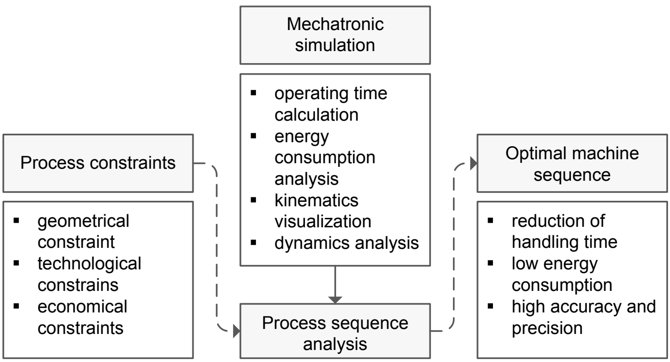

Figure 51: The process sequence optimization of the IR using the mechatronic simulation approach

The robot in the UCM cell is used for PCB handling, i.e. taking a PCB from one position to another. This process can be optimized using the mechatronic simulation approach by analyzing the robot's operating time, energy consumption, accuracy and precision, as well as its kinematics behavior (as shown in Fig. 51).

In the mechatronic simulation, the motion of the robot can be simulated in a virtual environment, representing the actual robot's motion. From this, the motion time can be calculated and analyzed. Furthermore, the energy consumption of the robot during its motion can be monitored, and the data obtained can be used to find energy-efficient approaches for the robot's motions. In addition, the mechatronic simulation approach also has the capability to monitor and analyze the accuracy of the robot motion. Thus, it can support the process planning of the system, while ensuring an ergonomically safe process and to find the optimum robot sequence by simulating several sequence alternatives.

6.3 Dynamics analysis of the industrial robot

Many of the robot's dynamics parameters, such as inertia, mass, center of gravity and control systems have a direct influence on the robot's performance. This behavior plays a very important role in order to improve the efficiency and the performance of the robot especially with regards to energy consumption. Thus, analysis of this behavior will provide better information for planning engineers to perform process planning tasks. In this section, the dynamics analysis of the IR is presented, which includes analysis of the robot torque, robot speed response and robot accuracy. Descriptions of these analyses are presented as follows.

6.3.1 Analysis of the robot torque

The robot's torque is a parameter that directly relates to the overall dynamics performance of the IR. It offers information on the robot's capacity for performing a handling task and determines the maximum payload that can be handled by the robot. The torque also gives information on the performance of the robot's control and mechanical systems, and how they deal with jerk and losses of the robot. In addition, the behavior analysis of the torques involved can help a planning engineer to analyze the robot's energy consumption since the torque has a strong correlation with energy consumption behavior.

Table 11: Simulation design for analyzing the influence of operating conditions on the robot's torque behavior

Parameters	Value and description
Investigated axis	axis 1, axis 2
Movement	90^{o} to -90^{o} of the investigated axis
Speed	10% to 100% of the maximum speed
Payload	1 kg, 3 kg, 5 kg

Based on the simulation results, the robot torque involved for the investigated axis is collected. To examine the torque behavior of the robot, simulation conditions are defined as shown in Tab. 11.

In order to analyze the gravitational effect, the experimental investigation also focused on axis 2. The movement is set from 90^o to -90^o of the investigated axis, while the other axes during the robot movement are set to their idle positions. To investigate the effect of the operating conditions on the torque behavior, the velocity is set to 10-100% of the maximum speed. A payload of 1-5 kg is attached at 15 mm from the end of axis 6 (see Tab. 11).

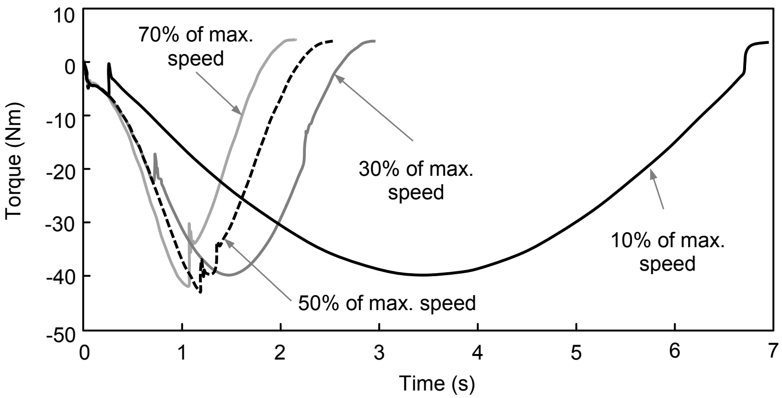

Figure 52: Influence of speed on the robot torque (axis 1, payload 3 kg)

Robot speed is one of the main parameters that has a strong influence on the robot's torque. Based on Fig. 52, the maximum torque of axis 1 at speeds 10-30% of the maximum is 40 Nm (the negative values indicate the direction of the robot motion). However, higher operating speeds (from 50% to 90% of the maximum) show that the torque increases further due to jerks and vibrations. The oscillations on these graphs are caused by the change of the robot speed and acceleration's profile. Thus, these results suggest to the planning engineer, that the operating speed of the robot should be set at low speeds to maintain low values of torque with minimum vibration.

The influence of the robot payload on the torque is shown in Fig. 53. This characteristic of the curves show that higher payloads lead to higher robot torque. This phenomenon is in accordance with the mathematical equation of the torque, whereby the torque is a function of the payload and distance. In order to evaluate the simulation results, an analytic calculation of the robot torque is performed. For this study, the analytical calculation method is conducted using equations from [145]. As was predicted, the maximum torque using analytics and simulation method is same.

The only difference is analytic calculation cannot shows the fluctuation in a robot torque. Furthermore, Fig. 53 also shows that higher payloads lead to higher fluctuations of the robot torque, which are occur in beginning and end of a new robot speed profile.

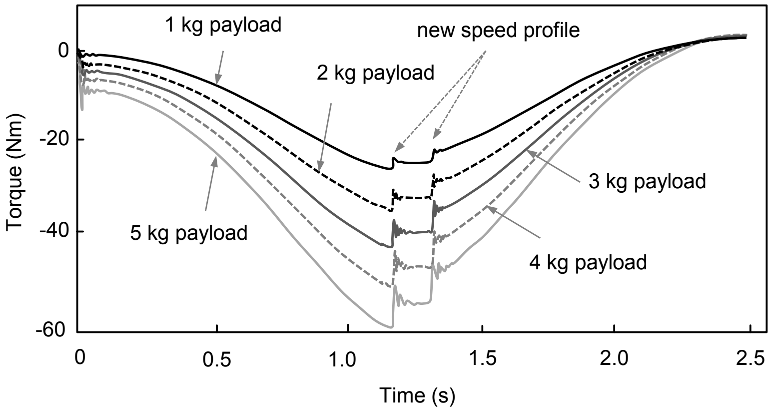

Figure 53: Influence of the payload on the robot torque (axis 1, 50% of maximum speed)

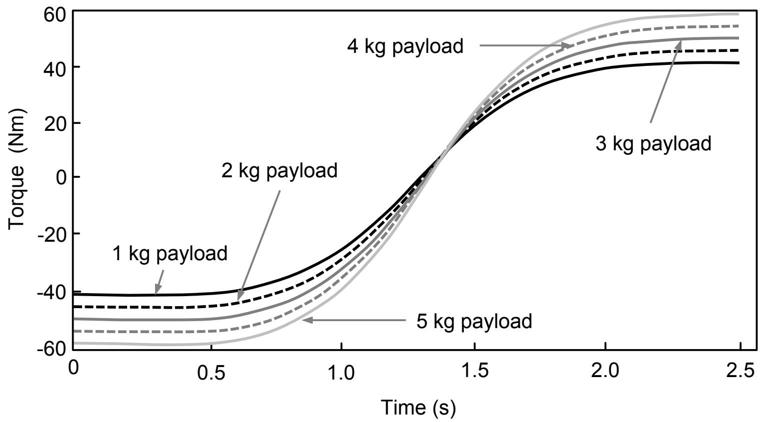

Figure 54: Influence of the robot gravitational load on the robot torque (axis 2, 50% of maximum speed)

Moreover, the simulation results found that axis 2 registered a maximum torque of about 58 Nm, which is used to maintain the position of the axis to counter the gravitational load. It also shows that higher payloads result in greater gravitation loads (as shown in Fig. 54). Therefore, this suggests that the robot can better perform with lower vibration through the use of smaller payloads.

In addition, the investigation yielded information on the position of the payload and its huge influence on the robot torque. For this investigation, payloads mounted near axis 6 produced smaller torque. Therefore, preference was given to installing the payload as near as possible to the end of axis 6. Thus, lower torque can be achieved when the material is located as near as possible to the end of axis 6. The gripper to handle the material should then be designed accordingly.

6.3.2 Analysis of the speed response

The simulation model can also be used for analyzing the speed response of the robot arm. The speed response analysis will give a clearer picture of the robot's jerks and vibration. Therefore, this investigation yields benefits to the planning engineer for defining the optimal operating conditions of the IR, i.e. high accuracy and low energy consumption.

Due to its large vibration compared with other axes, this investigation focuses around axis 6. The simulation result is shown in Fig. 55, which illustrates the response speed of this robot axis within the first minute under several operating speeds and payloads. Information from Fig. 55a indicates that the speed of the robot has no significant influence on the robot response speed. Also, the oscillation of the response at the beginning of the robot's motion is relatively minimal. The model of the control system of the robot was able to compensate for the fluctuation very well by reducing excessive acceleration. [2] [10]

In contrast to the study on the effects of maximum speed, the payload of the robot has significant influence on the robot speed response (as shown in Fig. 55b). Similar to the previous graphic, this figure represents the response speed of the robot within the first minute under different payloads. The trends indicate that heavier payloads lead to higher response speeds at the beginning of movement. The reason for this is that heavier payloads also produce higher torques (as shown in Fig. 53). Thus, the robot motor drive requires more power to accelerate the motor shaft, resulting in greater acceleration which can be seen at the beginning of the movement. Hence, this suggests that reducing the robot payload can be applied in order to reduce the oscillation of the response speed.

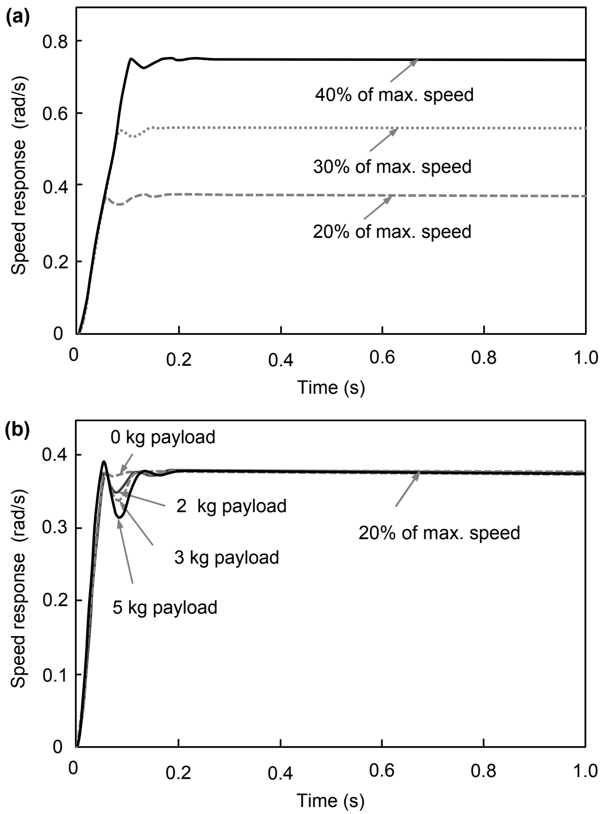

Figure 55: Response speed of the robot under several speeds and payloads at axis 6 [2] [10]

6.3.3 Analysis of the robot accuracy

The accuracy analysis is performed by comparing the desired position and the actual position of the joint axis. The desired position is gained from the path planner via the control bus, which delivers the target path in angular coordinates. On the other hand, the actual position is measured from the mechanical structure during robot movement.

Table 12: Simulation set-up for analyzing the influence of robot speed and payload on the robot accuracy

Parameters	Value and description
Investigated axis	axis 1 and axis 6
Movement	axis 1 (45^o to -45^o; axis 6 (-90^o to 90^o)
Speed	10% and 100% of the maximum speed
Payload	1 kg, 3 kg, 5 kg

In order to investigate the influence of the robot's operating parameters on robot accuracy, an experiment is set up as defined in Tab. 12. As shown in the table, the investigation is focused on axis 1 and 6; while the position for the model is defined as from 45^o to -45^o for axis 1 and from -90^o to 90^o for axis 6. Besides this, the robot speed is simulated at 10% to 100% of the maximum speed, and the payloads used range from 1-5 kg.

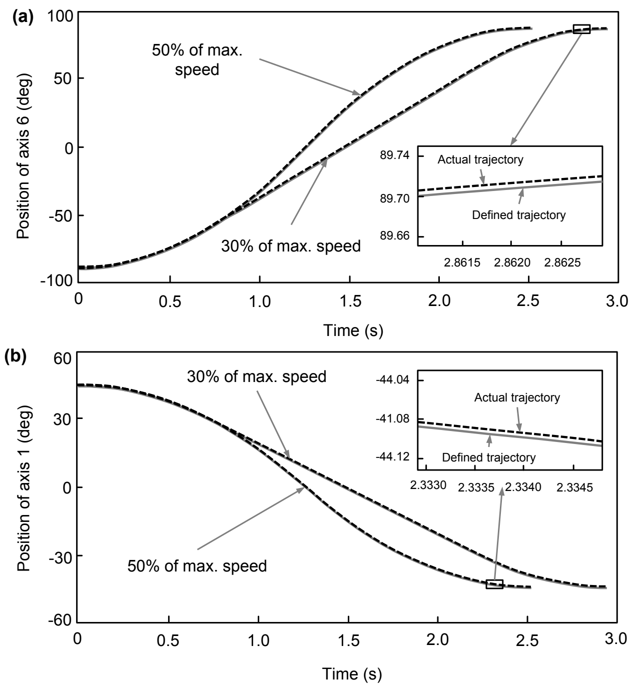

Figure 56: Influence of the robot speed on the robot accuracy

The investigation results reveal that the average deviation between the desired positions with the actual position is about 0.00419 degree (0.073 miliradian) for axis 6 and 0.00349 degree (0.061 miliradian) for axis 1. As seen in Fig. 56, the influence of the speed on the accuracy is not too significant. For example, the accuracy of the axis 6 at 30% of maximum speed is given at 0.00475 degree, while the accuracy at 90% is 0.00384 degree. Similarly, the accuracy of axis 1 at 30% of maximum speed is 0.004581 degree, while at 90% it is 0.005295 degree.

This study verifies that the simulation model of the motor control system performs robustly and sufficiently to control the effect of speed variations. Based on these results, planning engineers can operate the robot at energy-efficient speeds without compromising on robot accuracy. Nevertheless, the lower speed is suggested for tasks that require a high degree of accuracy. At very low operating speeds (about 10%) the deviation is minimal, which is less than 0.001 degree (see Fig. 57).

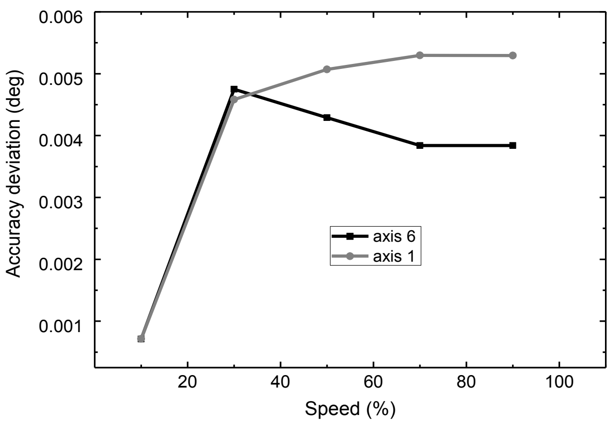

Figure 57: Accuracy deviation of the robot at several operating speeds (payload 3 kg)

In addition, the investigation results found also that the payload has no significant effect on the robot accuracy (see Fig. 58). While higher payloads lead to higher deviation of the accuracy (low accuracy), the deviation error remains minimal. For example, at 1 kg payload the deviation is at 0.004392 degree and for the 5 kg payload it is at 0.005573 degree. Thus, the control systems of the robot can continue to robustly maintain the accuracy of the robot position under several operating payloads.

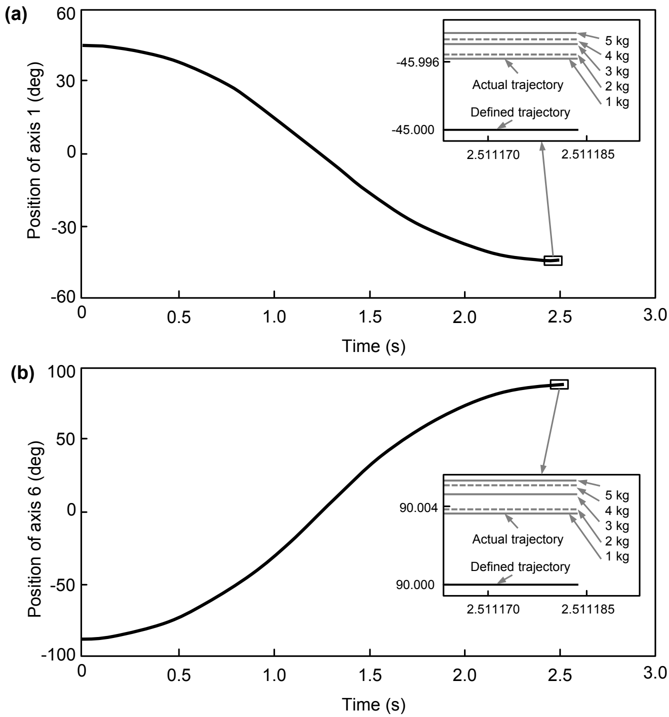

Figure 58: Influence of the robot payload on the robot accuracy

6.4 Summary

Kinematics and dynamics behavior analyses of IR lead to a better understanding of robot performance, with acquisition of information on accuracy, repeatability and energy consumption. The kinematics analysis of the machine is usually performed using CAD software, with emphasis on collision avoidance, process sequencing and work space identification. In contrast, dynamics analysis is performed by using dynamics simulation software packages that have the capability to model and simulate the robot's control system. However, these two types of simulation are performed separately in conventional simulation approaches. To address this issue, the mechatronic simulation is able to integrate kinematics and dynamics analyzes, as presented in this chapter.

Furthermore, it is clear that involving these analyses in the process planning of IR helps the planning engineer to develop and decide on an effective method for reducing energy consumption. The chosen method should not only have a high effectivity for reducing energy consumption, but it must also do so without sacrificing significantly the performance of the robot.

In this chapter, the kinematics analysis is used to describe the motion of every robot joint and arm that is gained from the simulation model. The analysis focuses on the layout analysis, collision detection and process sequence optimization of the IR. Using the mechatronic simulation approach, the position of the robot arms during robot operations can be monitored. Thus, potential collisions that may occur can be detected. Furthermore, the robot process sequence can be optimized and the motion path and duration time of the IR can be analyzed to find optimal process sequences. In addition, the use of kinematics analysis allows planning engineers to select the best possible process among several simulated handling alternatives and ensure that the process is safe for humans as well as fulfils any ergonomic requirements.

Furthermore, the dynamics behavior analysis that was presented in this chapter is focused on robot torque, speed response and accuracy analysis. Based on the investigation results, it is found that the robot operating conditions correlate strongly to the torque, speed response and the accuracy of the robot. The dynamics behavior of the robot shows that there are optimal operating conditions that can be chosen by a planning engineer to improve performance of the robot. For example, by planning to use smooth motion, the robot will have better response speed, thus leading to better robot accuracy. Simulation results also show that the robot dynamics behavior is greatly affected by the mass of the robot structure and the payload applied on the robot links, as well as the position of the payload. Therefore, the position and shape of robot gripper and the payload will have a huge influence on the robot's performance. Thus, a centered and well-balanced gripper is suggested for better performance of the IR.

However, due to the technical issues, i.e. the robot motions are too narrow and there are many layout constraints, an experiment validation of the speed response and the robot accuracy are hardly to be conducted. As a solution, in this analysis, the validation for the simulation results is conducted by comparing the input parameter of the robot with the actual condition of the robot. By using this method, the deviation of the simulation results can be evaluated.

To summarize this chapter, the investigation results prove that the simulation model is effective for analyzing the robot's dynamics behavior in order to support the process planning of IR. Using the mechatronic simulation model, the planning engineer can thus implement energy-conserving methods without jeopardizing the performance of the IR.

7. Energy Consumption Analysis of the Industrial Robot

In this chapter, the energy consumption analysis of the IR is presented, with focus on the discussion of the effect of robot operating parameters on its energy consumption. The chapter begins with a description of the power flow of an IR that is used in HS. Next, the influence of the robot operating parameters on the energy consumption is presented in Section 7.2. This includes the effect of the robot operating speed, robot payload and robot acceleration on the energy consumption. In Section 7.3, the effect of the robot dynamics on its energy consumption behavior is evaluated. The dynamics parameters such as mass, gravity, elasticity and damping are described. Finally, to conclude this chapter, a summary and remarks are given in Section 7.4.

7.1 The energy consumption analysis of industrial robots

IR are the handling machine that have significant influence on the energy consumption of HS since many of the modern automated HS are equipped with at least an IR. Therefore, for reducing and optimizing the energy consumption of HS, the energy analysis of IR is expected, especially in the mechatronics and automotive industries, where IR are extensively used.

As mentioned in Chapter 1, reducing the energy consumption of IR will reduce the operational costs of the HS. For instance, a 10% reduction of the energy consumption of the robot enables companies to reduce the cost for their electrical energy that used for handling systems up to 5% since up to 50% of the energy consumed by HS is taken up by the IR.

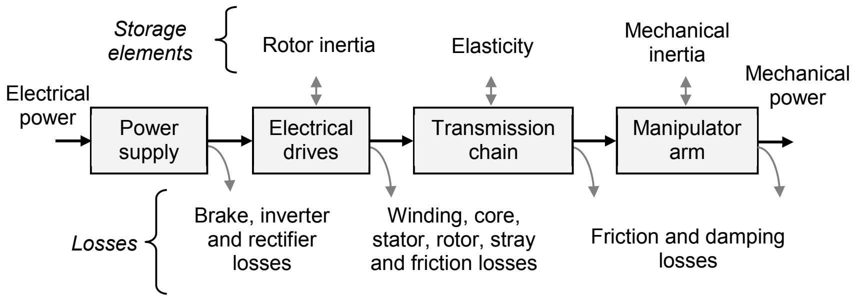

Figure 59: Power flow diagram of IR [116]

The energy consumption analysis of the IR is conducted by describing its electric power flow. As shown in Fig. 59, the power flow of the robot is very complex. However, mechatronic simulation can be effectively used to analyze the relationship among the robot components with regards to the energy consumption. Mechatronic simulation facilitates the analysis of the power usage of every robot component. Thus, correlations of the influencing factors, such as robot control systems and robot operating parameters can be better understood.

As shown in Fig. 59, the power of an IR comes from the electrical supply and flows to the robot motor drives via the power supply unit. The electrical energy then is converted by electrical drives to mechanical power in the form of torque and speed. From the electrical drive shaft, the mechanical power then is delivered via the transmission to the manipulator arm. This mechanical power is used by the arms to handle the material work piece. Alternatively, in many cases a special effector is used (e.g. welding torch or painting spray).

Every robot main component contains two elements called *storage elements* and *losses*. Storage elements are not real components but are the physical behavior of an IR component that is used for storage of the energy either in the form of mechanical or electrical energy. In the electrical drive, the storage elements can be rotor inertia and the winding inductance. In the case of the robot's transmission, the elasticity of the damper and spring are the storage elements. For the manipulator arm, the mechanical inertia is the storage element since it is able to store the mechanical energy. On the other hand, the losses are the power (in the form of electrical and mechanical power) that dissipates or disappears during power flow. As mentioned in Section 4.6, the losses can occur throughout every robot component. Losses in power supply include brake, inverter and rectifier losses; losses in the electric drive are winding, core, stator, rotor, stray and friction losses; and losses in transmission are friction and damping. All of these storage and losses elements should be modeled at a high level of accuracy in order to build an accurate IR model.

The mechanical power of IR is mainly dependent on three parameters: robot torque (T), angular velocity (ω) and the electrical and mechanical coefficient (η_{el}, η_{mec}), which represent the losses in the mechanical and electrical components. Therefore, the mechanical power of IR can be formulated as shown in Eq. 16, while the energy consumption (W) is the integral of the power over time $0 \ldots t_f$ as shown in Eq. 17. [10] [146] [147]. Eq. 16 shows that the mechanical power can be reduced by decreasing the speed of the robot motion. However, the energy consumption is also a function of operating time; this means that at lower speeds, the operation needs longer operating time and tends to result in higher energy consumption. Thus an optimization is needed to ensure that IR are operated in energy-efficient conditions.

$$P_{mech} = \sum_{i=1}^{n} T_i \omega_i \frac{1}{\prod_{i=1}^{n} \eta_{mech,i} \eta_{el,i}} \tag{16}$$

$$W = \int_0^{t_f} P_{mech} dt \tag{17}$$

where n is the number of robot axis, T_i is the torque applied to the ith axis, ω_i the angular velocity of the ith axis, $\eta_{mec,i}$ and $\eta_{el,i}$ mechanic and electric efficiencies of the ith axis drives, respectively [147].

In the context of the energy consumption calculation, using the mechanical power as the basis is not valid, except for analyzing the mechanical energy losses. The reason for this is that there are many losses that occur before the energy flows to the robot structure. Thus, calculating the energy consumption using its mechanical power is not accurate. This is also the reason why many commercially developed models cannot predict the energy consumption behavior of the robot at a high level of accuracy.

Therefore, the energy consumption should be calculated from the robot electrical values since it represents the real energy consumption. Moreover, the electrical energy calculation enables the author to perform validation since only electrical power can be measured experimentally. Using this method, the electrical power consumption is calculated based on the value of the voltage (U) and current (i) that flows into robot motor drives. However, besides these values, IR also require power for their control and power supply unit. Thus, the electrical energy consumption of IR can be formulated as:

$$P_{el} = UI + P_{losses} \tag{18}$$

$$W = \int_0^t \sum_{i=1}^n P_{el} dt \tag{19}$$

where I and U are the equivalent DC current and voltage of the motor.

Theoretically, the calculation results of the energy consumption of the robot using Eq. 17 or 19 should be the same, since the energy input should be equal to the energy output, based on the law of conservation of energy. However, in actual cases the values are different due to energy losses. In other words, electrical power represents the energy consumption, while the mechanical power consumption represents the real work done. Thus, Eq. 16 and 17 are only suitable for evaluating the robot's losses, especially for calculating the effect of the friction and damping of the robot transmission.

7.2 Influence of the robot operating parameters on the energy consumption

The decision to choose the value of the operating parameters of IR is the main part of the process planning task. Accordingly, in this section the analysis of the robot operating parameters on the energy consumption is conducted. The analysis includes the influence of robot speed, acceleration, robot payload and the robot trajectory on the robot energy consumption. For this purpose, data from the simulation and experimental results is used.

7.2.1 Influence of the robot speed on the energy consumption

To define operating speeds of an IR, a process engineer considers at least three factors, i.e. productivity requirement, robot layout and the robot payload. Productivity is the factor that determines the production rate of the handling process and is the main influence factor. Hence, to have a high production rate, IR are often operated at their maximum speed without considering the effect on energy consumption. The decision to choose the robot operating speed is based mainly on the knowledge of the engineers, which in many cases means that the speed is not set at the robot's best performance and best energy-efficient conditions. Thus, there are huge opportunities to reduce energy consumption of IR by optimizing the robot operating speed since operating the robot at their maximum speed leads to higher energy consumption [2] and higher wear.

Beside this factor, planning engineers will also consider the layout since in many handling processes; the robot should be able to handle a material passing through a narrow gap. Thus, they need to reduce the speed of IR to ensure that the processes are free from collisions. Furthermore, in several handling tasks, IR are operated at their maximum payload allowed. This condition leads planning engineers to operate the robot at very slow speeds to ensure that the robot has no problem with regards to its motor drives and structures.

Table 13: Simulation set up for analyzing the influence of robot speed and payload on the robot energy consumption

Parameters	Value and description
Investigated axis	axis 1
Movement	-90 to 90, other axes 0 to 45
Maximum speed	10% to 100% of the maximum speed
Maximum acceleration for axis 1-6	15, 15, 15, 30, 30, 30 rad/s^2
Payload	3 kg

Because of this, analyzing the influence of the robot operating speed on its energy consumption is needed in order to find the optimum speed. Therefore, a set of conditions are simulated, which is shown in Tab. 13.

In this analysis, the effect of the operation speed of the robot movements was measured by means of a movement of axis 1 from 90^o to -90^o, while all other axes were moved from 0^o to 45^o. The influence of the operating speed was measured by varying the robot speeds from 10% to 100% of its maximum value, while the maximum acceleration was set to 15 rad/s^2 for axes 1, 2, 3 and 30 rad/s^2 for axes 4, 5, 6 in order to ensure that the robot can reach the desired speed.

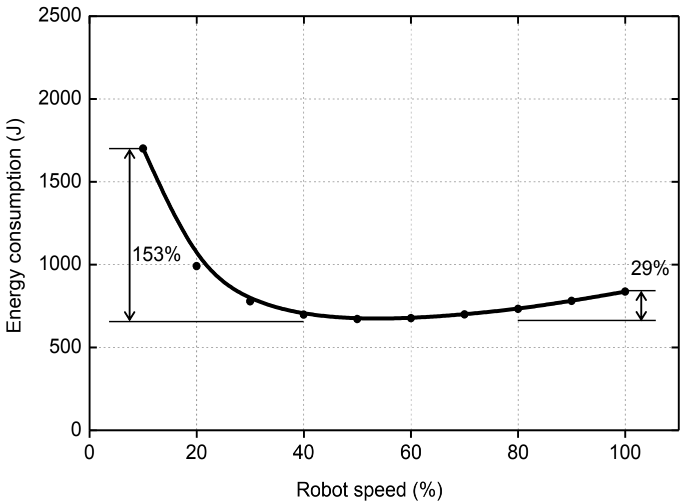

Figure 60: The energy consumption of the IR under several operating speeds

The result from this investigation is depicted in Fig. 60. The figure shows that the speed of the robot movement has a strong influence on the energy consumption of the IR. Very high and very slow robot speeds will lead to higher energy consumption, while medium robot speeds consume less energy. Based on the investigation results, operating the robot at 50% of its maximum speed is the most energy-efficient, compared with the other speed values. This is because at that speed, the power consumed is relatively low and the time that is used to accomplish the task is relatively minimal. However, the difference of needed energy from 40% to 70% of maximum speeds is not significant. Thus, when the productivity is the main factor in a handling process, operating the robot at 70% of maximum speed is suggested in order to improve handling productivity rate.

Fig. 60 also shows that lower speeds, e.g. 10-20% of its maximum speed will consume low power but need longer time to accomplish the given task, leading to very high energy consumption. Contrary to the low speed conditions, high operating speeds (e.g. 90-100% of the maximum) need more power in order to operate the robot motor at higher speeds and to accelerate the motor at the beginning of the motion. As follows, these operating speeds are not suggested for energy-efficient handling processes.

The power profile of the robot at several operating speeds at its first second is shown in Fig. 61. It clearly shows that power of the robot is linear with the speed value, that is, higher speed needs higher power. At the beginning of the movement the power consumption is high due to the acceleration effects. The simulation results also indicated that at the end of the movement, there is jerk that occurs along the robot axes, which is caused by the deceleration effect. Therefore, optimizing the speed of the robot not only will reduce the energy consumption of the robot but also will reduce the vibration and jerks of the robot structure.

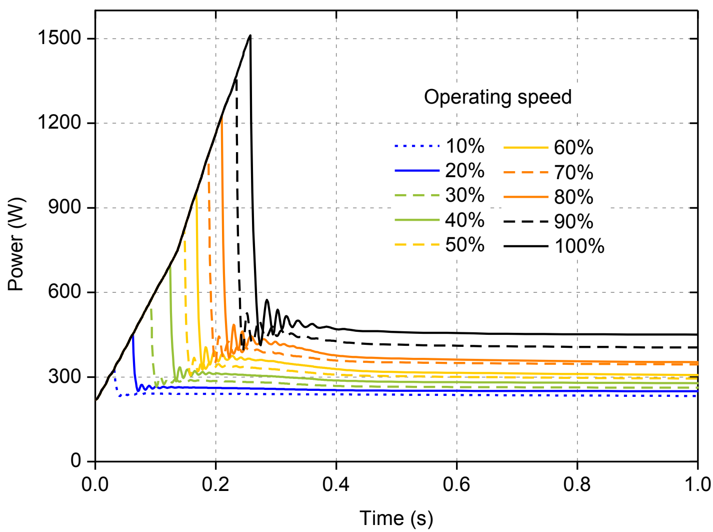

Figure 61: Power profile of the robot at several operating speeds

The measurement results indicate that the power that is used to operate the supporting components such as the control unit and the PC is about 220 W. This fact means that at lower speeds the electrical power is used mainly to operate the robot's supporting components and to maintain the position of the robot axes, while at higher speeds, the electrical power is mainly used to rotate and accelerate the robot motor drives.

The power consumption behaviour represented by the current that is needed by every axis is shown in Fig. 62. As can be seen in the figure, motor drive axis 1 and 2 need higher current to operate the motors than the other axes. The reason for this is that axis 1 has a greater distance to cover and at a higher velocity, while axis 2 needs more power to bear the gravitational load. However, the simulation result also shows that even for immobile robot axes, the motor still needs an amount of electrical current to maintain the position of the robot arms.

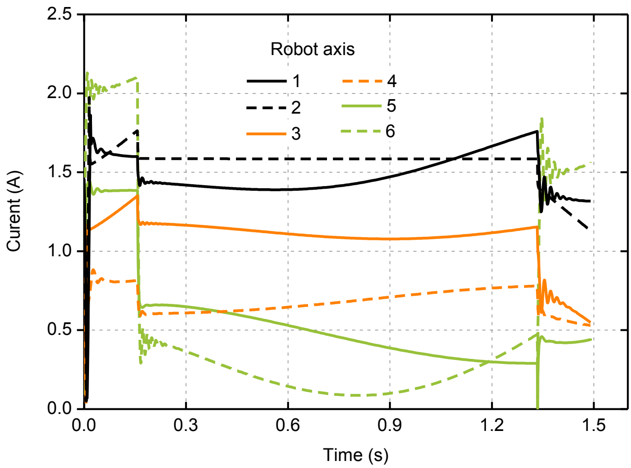

Figure 62: The current behavior of the motor on all motor axes (at 50% of maximum speed)

This phenomenon can also be observed in the energy consumption profile. Here, axis 1, which has a greater degree of motion than the other axes, accounts for a large share of the total energy consumption. Similarly, axis 2 shows similar behaviour, as this axis is bearing the gravitational load (see Fig. 63).

As mentioned before, the execution time is also a crucial factor in the process planning of IR. Hence, in this analysis, the execution time is also investigated. The results are shown in Fig. 64. This figure shows that the difference of operating time between 50% and 100% of maximum speed is about 0.5 seconds. However, changing the robot speed from 100% to 50% of the maximum is able to reduce the energy consumption of the robot by about 19.7%. This means that operating the robot at a maximum speed of 50% will reduce the energy consumption, but will increase the operating duration. Thus, without considering the production rate, a medium operating speed, around 40-70% of the robot's maximum speed, is suggested.

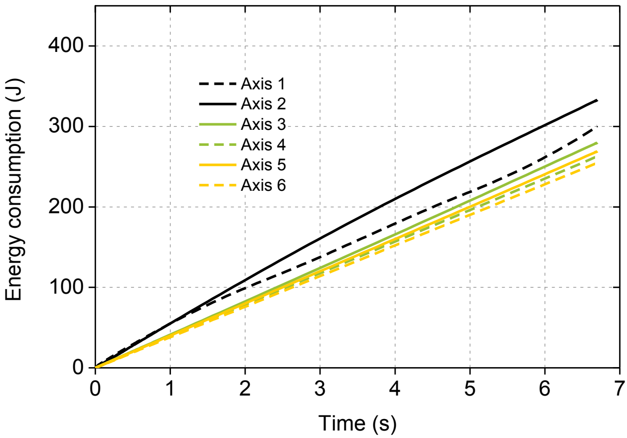

Figure 63: Energy consumption of every robot axis at maximum speed 10%

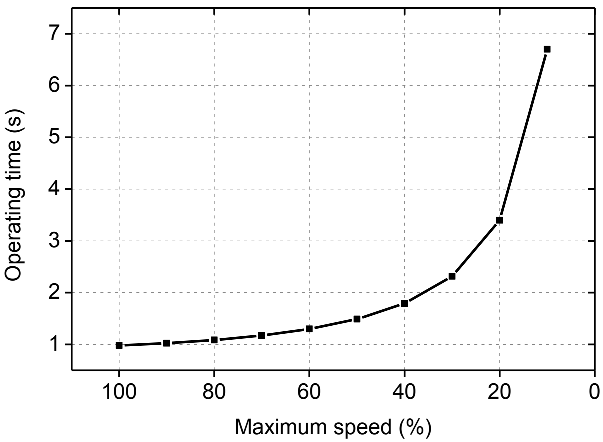

Figure 64: Execution time for different maximum operating speeds

Based on the simulation results, it is also suggested to operate the robot at medium speeds for a constant period, rather than at higher speeds but pausing before the next sequence. This is because the robot consumes more energy when accelerating from the standby position.

7.2.2 Influence of the robot acceleration on the energy consumption

Based on the simulation results that are presented in 7.2.1, it can be shown that the robot's acceleration has a huge impact on the robot energy consumption. Thus, it is necessary to analyze the influence of the robot acceleration in greater detail.

In the previous investigation, the value of the maximum acceleration was always set to a specific value (e.g. 15 rad/s^2) since in modern control systems there is also limitation of the acceleration of the robot movement [148]. However, in many robot systems, IR are typically instructed to accelerate as fast as possible until they reach the desired speed and then decelerating rapidly to a standstill mode once the target has been reached [92]. Therefore, it is suggested to analysis of the influence of robot acceleration on the energy consumption, in order to gain deep knowledge concerning the energy behavior of IR. This investigation should provide insight on the possibility for reducing the energy consumption of IR by controlling the acceleration of the robot by limiting the maximum speed allowed. To accomplish this investigation, an experimental investigation and a simulation set is performed for several values of the robot's acceleration.

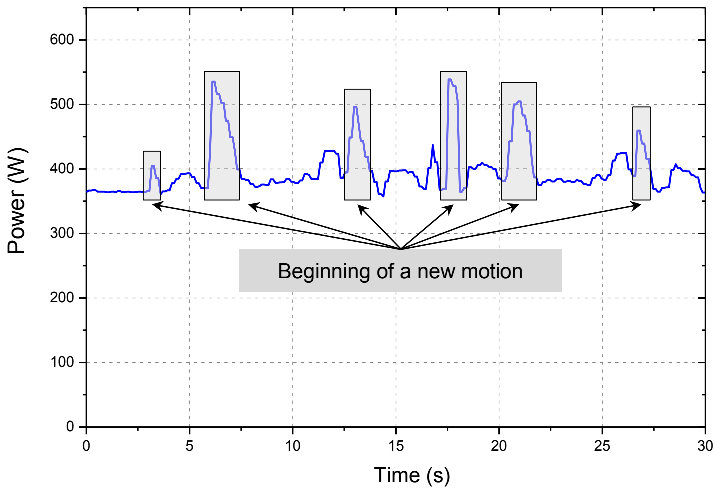

Figure 65: The energy consumption behavior of the robot as a result of motor acceleration [2]

Based on the experimental measurements, the robot acceleration does indeed influence the power consumption. At the beginning of the robot motion, energy consumption is high due to motor acceleration, as depicted in Fig. 65. The acceleration at the beginning of the robot motion also leads to jerk, since the value of the torque fluctuates before increasing. This vibration reduces the accuracy of the robot and leads to an increase of the energy consumption of the robot.

In Fig. 65 and 66, the effect of the acceleration on the energy consumption can be clearly seen. Furthermore, the simulation results as depicted in Fig. 67, confirms that increasing the maximum acceleration allowed also leads to higher power consumption. However, higher acceleration means faster robot movement, allowing it to accomplish the given task in a shorter period of time. Due to this, a limitation of the maximum acceleration/deceleration allowed should reduce robot vibration as well as reduce energy consumption.

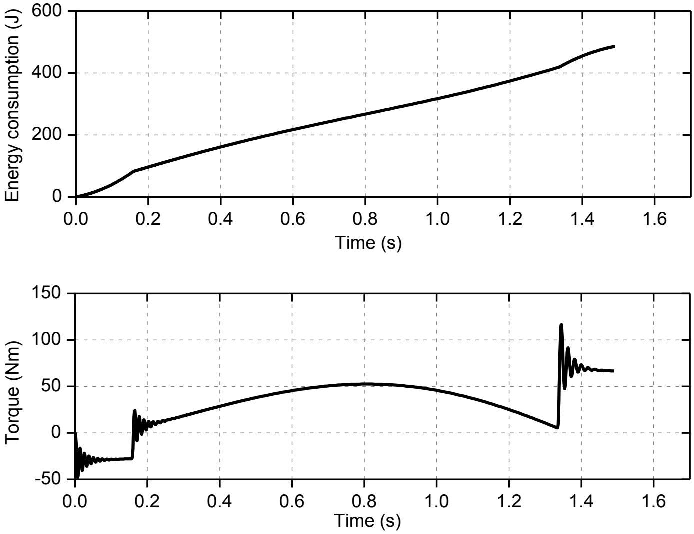

Figure 66: Influence of acceleration on the robot torque and energy consumption on axis 1 (at 50% maximum speed)

Furthermore, it can be concluded that energy consumption of the robot can be reduced by smoothing the robot motion, that is, by avoiding direct path or rough motion (much acceleration/deceleration). This is because, at the beginning of every new motion, the robot needs to accelerate the motor drives, which means that it needs more power (see Fig. 68). Based on these simulation results, the potential energy reduction by smoothing the robot motion is up to 20%. Thus, implementing this method (i.e. smoothing the robot motion) will give a significant reduction to the robot's operation cost.

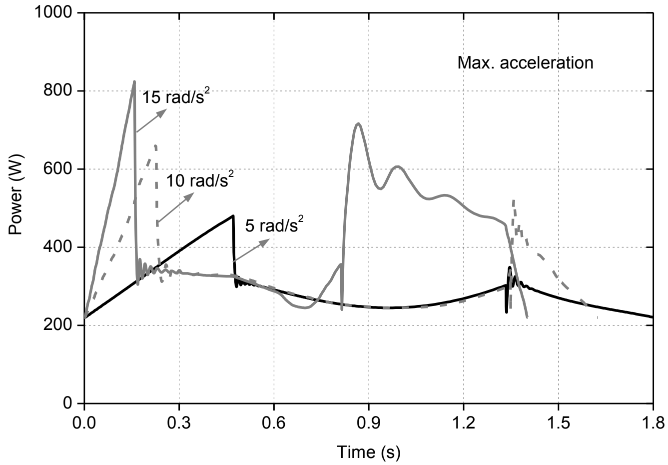

Figure 67: The power behavior of axis 1 at several maximum accelerations

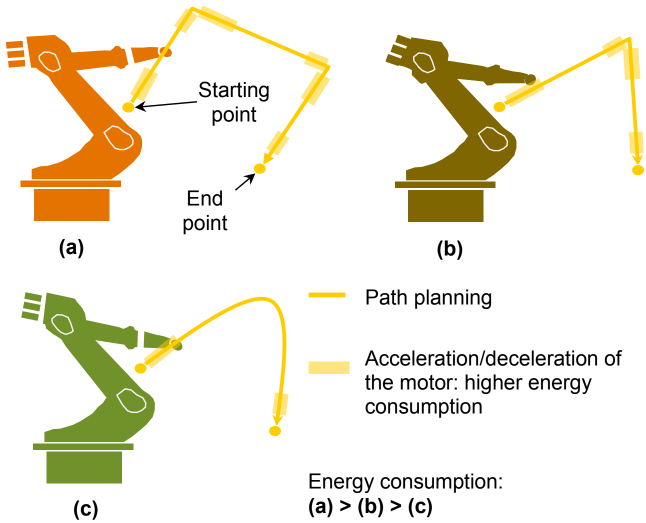

Figure 68: Smoothing IR motion for avoiding excessive energy consumption during the beginning of the motion [2]

Among the advantages of this method is its flexibility - that it can be implemented in both simple and complex handling processes. Nevertheless, based on the investigation results, it is more conveniently implemented in HS that consist of only one or two robots, which are in general more flexible in their processes, with only minor loss of the productivity rate.

Furthermore, the method can be used for optimizing the speed and acceleration profile of the robot motion without changing the layout constraint. The optimization can be done by planning engineers without needing to change the trajectory of the robot or the sequence of robot operation. This can be done for example by avoiding the excessive energy consumption by slowing down the speed and reducing the idle time of the robot. Therefore, planning engineers need not change the trajectory of the robot operation, but instead just optimize the timing of the motion and at which speed the robot should be operated in order to reduce the idle time.

7.2.3 Influence of the robot payload on the energy consumption

Based on the equation for mechanical power, a higher payload will lead to higher mechanical torque and thus higher energy consumption. However, in terms of IR, as complex mechatronic systems, a correlation between the payloads on the energy consumption is complex, since this is also dependent on speed, friction, the energy storage components and the robot mechanical structure. Nevertheless, using the developed simulation model, a further investigation of the influence of the robot payload on the energy consumption is conducted.

Based on investigation results, the relationship between the payload and energy consumption at specific speeds is shown in Fig. 69. It shows that the payload has a different effect on the energy consumption compared to acceleration. At low speed (10%), lower payloads lead to lower energy consumption. At medium speed (50%), higher payloads lead to lower energy consumption. While at high speed (100%), higher payloads lead to higher energy consumption. These phenomena can be explained by the friction and the inertial of the robot, the value of which is dependent on the speed.

The characteristic curve of the friction speed is shown in Fig. 70, which indicates that friction torque of the robot is very dependent on the speed. At lower and high speeds, friction coefficients are higher than at medium speeds. For medium speeds, the friction torque is decreasing (see Fig. 70). Thus, the energy consumption of the robot caused by the friction torque is minimal.

Concurrently, the simulation results also indicate that at medium operating speeds, the effect of structure inertia, which can store mechanical energy, can reduce the needed torque. Accordingly, instead of increasing the energy consumption, heavier payloads reduce the energy consumption. While at higher speeds, the friction value increases; thus also leading to higher energy consumption.

The detailed investigation on the effect of friction on the robot energy consumption will be presented in the sub-section 7.3.2.

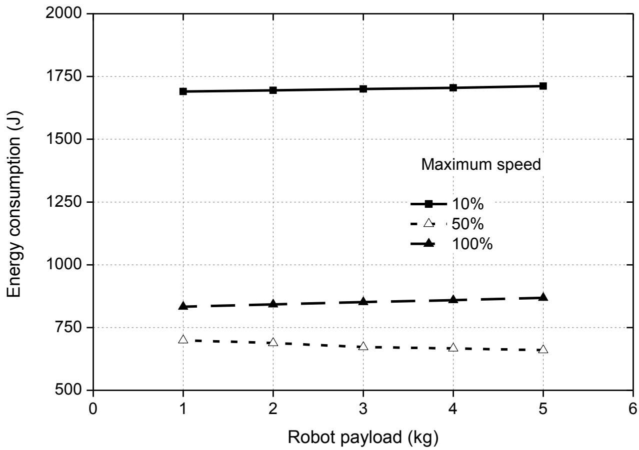

Figure 69: The correlation of robot payload and the energy consumption of the robot at specific speeds

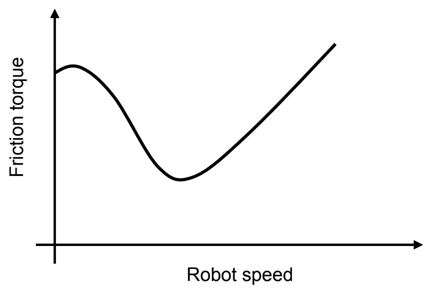

Figure 70: General relationship between friction torque and speed [148]

Furthermore, based on the current behavior, it is shown that at the beginning of the robot's motion, the current is relatively high (see Fig. 71b). The reason is that at the beginning of the robot motion, the motor drives need to accelerate the robot structure. However, after a few seconds of acceleration, the effect of the payload changes in contrast to the previous phenomena (see Fig. 71a). The heavier payload needs less motor current, as the result of the inertia, i.e. higher torque accounting for higher moment of inertia. This can reduce the friction of the robot structure. The mechanism of this phenomenon is principally similar to the flywheel effect that is used in an automotive engine.

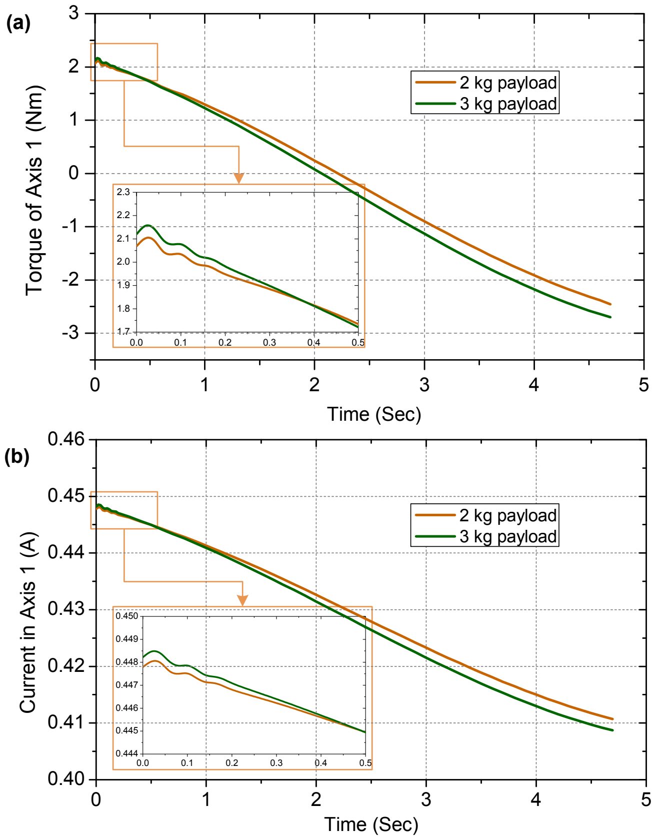

Figure 71: The torque and current in axis 1 with 2 and 3 kg payload [10]

The simulation results (as shown in Fig. 69) show that the difference of the values of the energy consumption of the robot at several operating payloads is slight. At very low and high operating speeds, an additional 1 kg payload contributes to a 5-9 Joule increase in energy consumption. This shows that in small robot systems, such as the Motoman MH5L, the payload has a minor influence on the energy consumption. However, operate the industrial robots exceed their maximum payload is not allowed. The reason is every industrial robot has its maximum value of the comparison between maximum payload and robot mass. Higher payloads, exceed the robot maximum capacity, will reduce the stiffness of the robot structure, and lead to the higher energy consumption. The investigation of this phenomenon is shown in subsection 7.3.2.

However, on medium and heavier IR, such as KUKA KR210 with a 210 kg payload, the payload has a huge influence on the robot energy consumption. This is because the current that is needed by the motor drives is greater in order to handle the heavier payload, thus leading to higher energy consumption. In these robot systems, the effect of friction has a minor influence on the robot energy consumption. Therefore, the reduction of the payload as well as the tool weight can significantly able to reduce the energy consumption of the robot. The effect is especially felt for medium and heavier IR. Reduction of the payload by 15 kg will reduce the energy consumption by about 0.4 Wh per cycle time (as shown in Fig. 72). Based on this, reducing the robot payload about 10% (15-20 kg) has the potential to lower the projected energy consumption by about 1.4% of the annual energy consumption per robot [98].

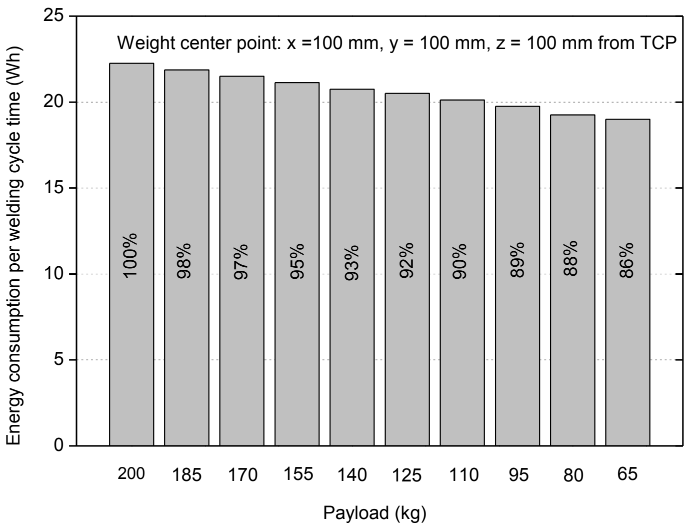

Figure 72: Energy consumption of the 210 kg robot under several payload conditions [98]

However, in many operating handling tasks, the weight of the handling material cannot be changed. Therefore, a planning engineering could instead reduce the required operating energy of the robot, for example by reducing the gripper weight by using lightweight materials.

In addition, the total weight of industrial robots also has a big influence to their energy consumption. An experiment from [98] shows that two robot system, KR16 (235 kg) and KR210 (1180 kg) with 16 kg payload and identical cycle time need different energy consumption. KR210 needs 2.2 times more electrical energy per cycle than KR16. This means that the weight of the robot has a strong influence on the robot energy consumption. Selecting appropriate industrial robots for a certain process can also able to reduce the energy consumption of HS.

Furthermore, based on the investigation results, the position of the payload also has an influence on the robot power consumption. The simulation results indicate that a payload center point closer to the end of axis 6 is able to reduce the robot torque and therefore the energy consumption of the IR.

7.2.4 Influence of the robot trajectory on the energy consumption

The trajectory of the robot motion has a significant influence on the robot energy consumption. The reason is robot trajectory defines the torque of the robot. Higher robot's torque will lead to higher energy consumption and vice versa. From the simulation results show that the industrial robot consume more energy when it is operated at big radius compare than operated in small radius. This phenomenon occurs both in a small robot (MH5L) and high mass robot (KR210).

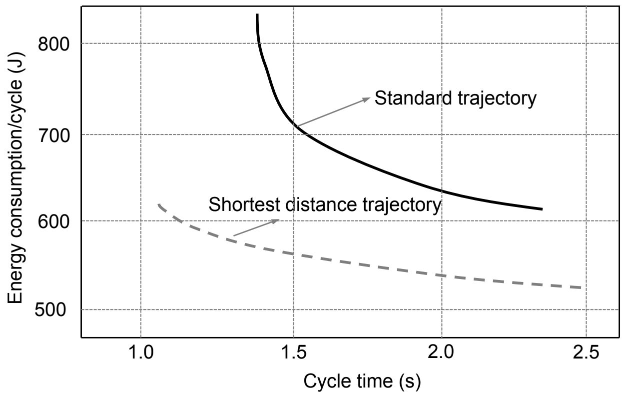

Figure 73: Energy consumption of an industrial robot at different trajectories [77]

Researchers that investigate the influence of the robot trajectory on the energy consumption also found this phenomenon (see [77] [149]). This mean that trajectory of the robot should be optimized to have a minimum energy consumption. Fig. 73 shows that choose a small radius of trajectory will able to reduce the robot energy consumption. Based on the literature review, that was described in Chapter 2, the energy reduction can also be conducted for example by changing the trajectory profile, time-scaling and modification of the part planning. Since there are many researchers that already discuss the influence of the robot trajectory on the energy consumption, in this dissertation, this sub topic is not described in more detail.

Beside aforementioned operating conditions that were described in sub-section 7.2.1-7.2.4, the energy consumption of industrial robots is also depending on several factors, e.g. frequent of start-stop robot’s operation [150], release braking strategy [99] and time scheduling [151]. Analysis of the influence of these factors on the industrial robot energy consumption is state of the art in this field of research, which is discussed on the author’s paper [2].

7.3 Influence of the robot dynamics parameters on the energy consumption

As presented in Chapter 6, the dynamics behavior of the robot has a great influence on robot energy consumption. Hence, in this section, further investigation of these influences is presented, with focus on the influence of gravity, robot friction and damping of the robot transmission on energy consumption.

7.3.1 Influence of the gravitational load on the energy consumption

The gravitational effect has a great impact on robot accuracy and robot torque. Therefore, much research has gone into investigating this parameter in order to find an effective solution for achieving high performance of the robot's system. To tackle this issue, research groups propose a solution by optimizing the control system of the robot, e.g. by optimizing the PD control system [152]. However, the existing investigations are still limited to the influence of the gravitational load on the robot torque behavior. An analysis of the direct influence of the gravitational load on electrical energy consumption has not yet been explored.

In the normal installation position (vertical position), a six-axis IR has to bear the gravitational load on axis 2, 3 and 5, while the gravitational load for axis 1, 4, 6 is relatively small and therefore can be treated as negligible. Thus, the investigation of the influence of the gravity load on the energy consumption is performed here by analyzing the energy consumption behavior of axis 1 and 2, since in axis 1 the gravitational load is relatively small compared with axis 2.

In relation to the gravitational effect, the simulation results are shown in Fig. 74. The curves indicate that axis 1 has only to bear the torque effect but axis 2 needs to compensate not only for the torque but also the gravitational load as well. The figure also indicates that the gravitational load for a small robot like MH5L is not so significant. However, in the heavier robot system, which has a greater mass, the gravitational load is very significant (as shown in Fig. 75) [116]. In that figure the experiment is conducted on the ABB IRB 6620, which is 900 kg in weight with a maximum handling capacity of up to 150 kg.

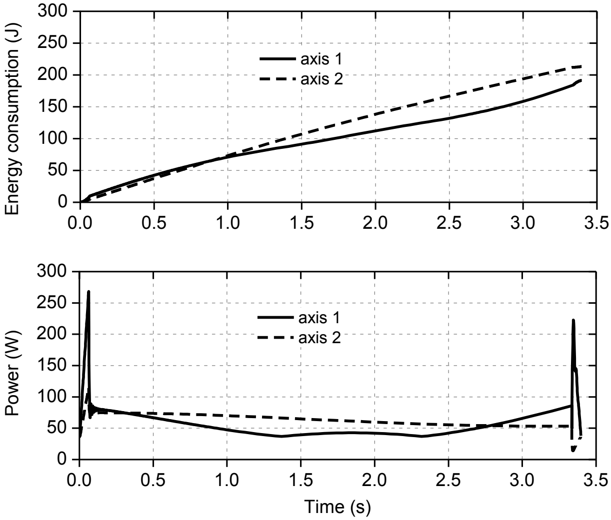

Figure 74: Effect of the gravitational load on robot power and energy consumption (at 20% of maximum speed and a 3 kg payload)

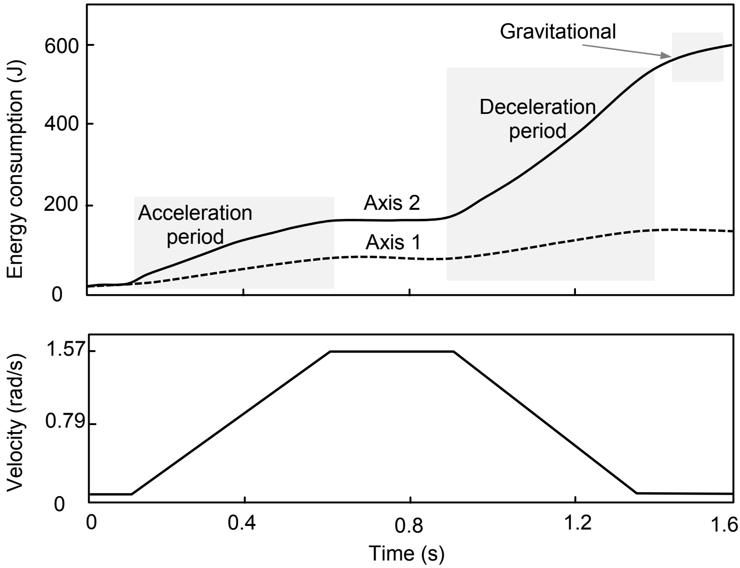

Figure 75: The effect of the gravitation load on robot energy consumption for ABB IRB 6620 [116]

The study shows then that the gravitational load has a major influence on the robot energy consumption in the medium and high-mass IR. Thus, the position of the installation of the robot also has a big influence on the energy consumption. Consequently, finding suitable positions for robot installation can also be used to reduce the energy consumption, which in many cases means the vertical position it is more energy efficient than the horizontal position. After considering process layout constraints, installing the robot on the vertical position is suggested, whenever possible.

This investigation results also indicate that during the standstill position, the robot needs a big amount of energy to maintain the position of the axis and to resist the gravitational load. Thus, it is suggested that a suitable standstill arms position be chosen, which requires small gravitational loads, when not in operation. Another solution, proposed in [148], for reducing the energy during standstill-mode, is by using a mechanical brake system for one or more robot axes. However, the amount of the energy reduced depends on the standstill duration. This means that when an IR is often in operation at the standstill-mode and for a long duration, it is suggested to implement this energy reduction method. Furthermore, since the brake mechanisms in many IR used to maintain the standstill position do so by using a permanent magnet or a spring-set brake system, early brake release is suggested to reduce the energy that is used for both holding the brake and counteracting the gravitational load [99].

While the gravitational load on the robot system leads to higher energy consumption, it also has the potential for reducing the robot's energy consumption. Particularly for high-mass robot systems, the gravitational load can be used to reduce the load of the motor drive when the robot arms are performing a downward motion. Therefore, this motion recuperates some energy. Since many motor drives employed in IR have two different modes, this can be performed by setting the motor drives in a generator mode instead of a motor mode. Future investigations, on the control strategy to optimize energy recuperation, should offer interesting insights.

7.3.2 Influence of the robot friction and damping on the energy consumption

The phenomena of friction and damping in IR occur primarily in transmissions, bearings, and joints of the mechanical arms. They are influenced by several factors, such as surface roughness topology, load, lubricant viscosity and temperature [153]. In a mechanical system, such as IR, the power consumption is proportional to the torque. Thus, friction and damping plays an important part in the energy consumption of the robot [148].

To investigate the influence of friction and damping, a simulation is performed on axis 1 (simulated from 0^{o} to 90^{o}), at 50% of maximum speed with a payload of 1 kg. The simulation result is depicted in Fig. 76. As shown in this figure, the difference of the energy consumption before and after passing through the transmission and bearing on axis 1 is about 45 J. Fig. 76 also shows that although the input energy is increasing (at period 0.2-0.6s), the output power is decreasing. This is because some of the input energy is dissipated and stored in the transmission and bearing components. Based on these facts, there is a potential of energy saving by optimizing the friction and damping condition of the transmission and bearing used by the IR. Nevertheless, energy consumption depends not only on friction and damping conditions but also on the operating conditions (e.g. speed) and the energy storage components (e.g. spring and damper).

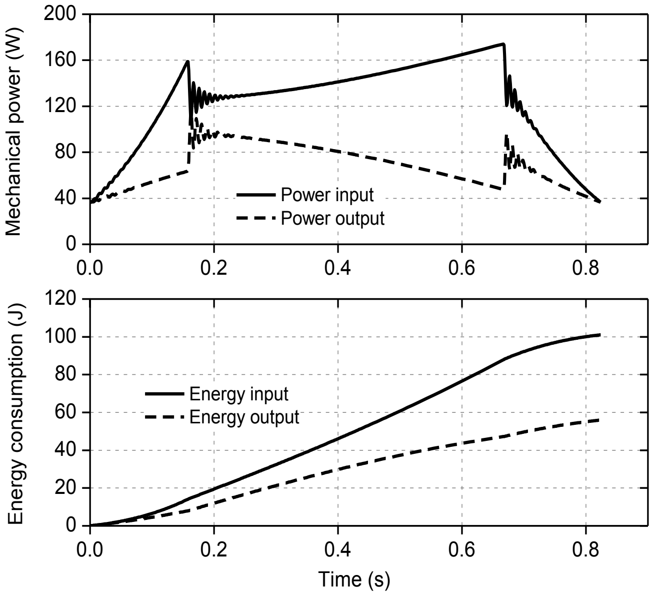

Figure 76: The difference of the mechanical power and its energy consumption before and after passing through the transmission and bearing

In order to investigate these phenomena, a set a simulations using the developed simulation model is conducted. The simulation is performed by varying the friction and damping coefficient of the robot transmission and its bearings. These coefficients represent the value of the damping and friction of real components. For example, the damping effects of the robot are mainly caused by the damper, lubrication and elasticity of the transmission, as well as the elasticity of the robot components. On the other hand, friction is mainly caused by the friction between components. In the Modelica® model, the initial value of the damping coefficient (d_0) for axis 1 is set for $6.635x10^3$ Nms/rad, while the elasticity/spring coefficient (c_0) is set to $3x10^5$ Nm/rad.

These values are chosen based on measurement data from Hardeman [154]. Moreover, the friction is modeled as viscous friction, which is dependent on the friction velocity. In this set up, viscous friction torque at zero velocity is set at 0.4 Nm and the viscous coefficient (f_0) set to 8.125 x 10^{-4} Nms/rad.

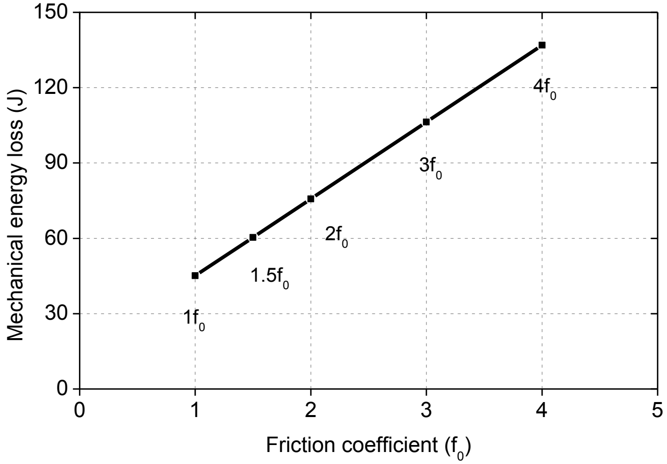

Figure 77: The effect of the viscous friction on the mechanical energy loss

The effect of friction that occurs in the IR in relation to its energy consumption is shown in Fig. 77. The figure shows that for every multiple increase of the friction coefficient, the energy loss increases by 30 J. This figure clearly shows that the higher the friction coefficient, the greater the energy loss. This shows that friction of the robot components has an influence on the robot energy consumption. Therefore, it is suggested that reducing the friction that occurs in robot systems is required in order to reduce the energy consumption of the robot.

The simulation results reveal that the variation of the damping and elasticity in the MH5L robot is not significant (as shown in Fig. 78). The reason for this is that the dimensions of the robot are relatively small, and the masses of the robot and the payload allowed are relatively low. Therefore, the effects of damping and elasticity on the magnitude of the robot's torque and the speed of the mechanical structure are not significant. Thus, the influence of the damping and elasticity of the robot transmission compared to the effect of friction on the energy consumption can be considered negligible. Furthermore, it can be concluded that the effect of the friction on the robot energy consumption is more significant than the elasticity and damping factor for small IR.

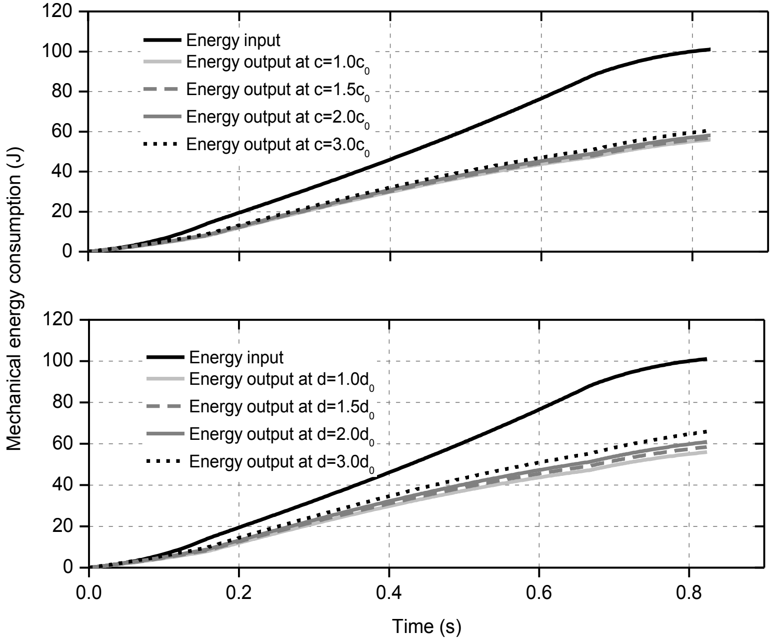

Figure 78: The effect of the damping and elasticity/spring to the robot energy consumption of MH5L robot

On the other hand, it is found these phenomena have an influence on the robot energy consumption for heavier IR. The analysis was done on the influence of the damping and elasticity effect on the robot model ABB IRB6620, which has a maximum payload capacity of 150 kg with a maximum reach of about 2.5 m. The investigations shows that at 50% operating speed, higher damping coefficients lead to lower energy consumption (see Fig. 79). The figure indicates that higher damping coefficients correlate to lower energy consumption due to a reduced fluctuation of the torque. The higher the damping coefficient, the faster oscillations decay. Therefore, the needed energy is relatively low. However, at very high damping coefficients (e.g. $5d_0$), the energy losses are also high due to the increase of dissipated energy.

At very slow speeds (e.g. 10%) and high speeds (e.g. 100%) the damping effects on the energy consumption are different. The higher damping coefficients lead to higher energy consumption since the friction torque caused by the damping effect at these speeds increases. This is confirmed by [152], which indicate that there is an optimal speed where friction torque is relatively low (as shown in Fig. 70). In this investigation, the optimal speed that produces lower friction torque is about 50% of the maximum speed allowed.

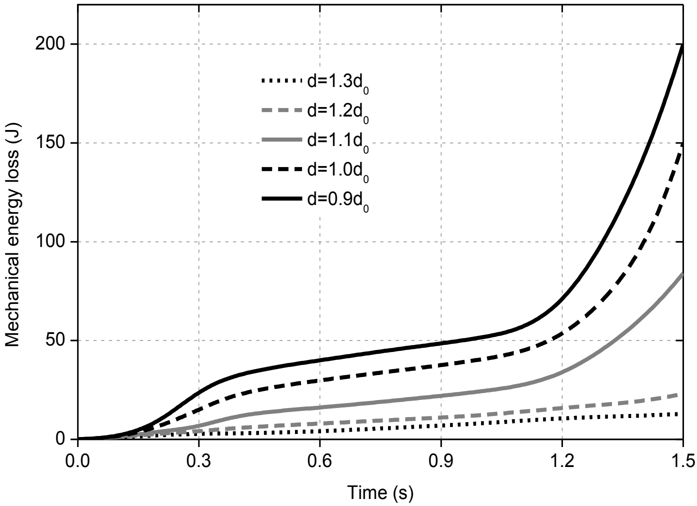

Figure 79: The losses of the mechanical energy at several damping coefficients

Contrary to the damping effect, higher values of joint elasticity (represented by coefficient *c*) result in higher mechanical losses (see Fig. 80). The more elastic the robot component, the higher energy is required. This is because the more elastic the robot components are, the greater the fluctuation/vibration of the robot structure is, which means that the amount of current of the motor drive that is needed to accelerate the robot structure will also be greater.

Furthermore, elasticity leads to oscillation phenomena that might form a source of inaccuracy. Thus, in order to reduce the energy consumption of HS, it is suggested to construct the IR with high stiffness, especially in its transmission and structure is suggested.

Based on the simulation results as shown in this section, the damping and friction has an influence on the IR energy consumption. Therefore, from the point of view of planning engineers, energy reduction can be achieved by choosing and/or adding additional damping or spring components or applying a suitable lubricant to the existing robot system for optimizing the value of the damping and friction coefficient. An alternative is to choose IR with a rigid structure and low friction coefficient.

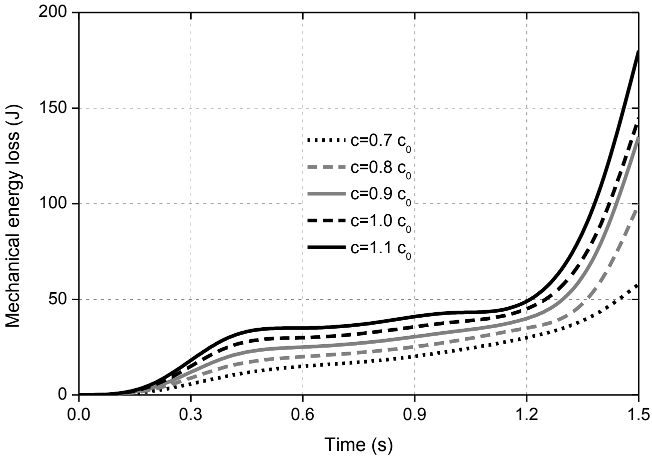

Figure 80: The effect of elasticity on the robot energy consumption

7.4 Summary

In this chapter, the energy consumption analysis of the robot under several sets of parameters is investigated. The first section discusses the energy flow of IR and the equations that represent the energy consumption of an IR. The energy losses and the storage elements from the robot main components are also presented. This evaluation is useful for engineers to get a better understanding concerning the energy model of the robot as well as the calculation of the robot energy consumption.

Control factors	Electrical factors	Mechanical factors
▪ Shape of trajectory ▪ Type of control systems ▪ Control gains and filters	▪ Type of the motor drives ▪ Motor losses ▪ Winding inductance ▪ Magnetic flux	▪ Damping systems ▪ Friction torque ▪ Elasticity of gear drive ▪ Rigidity of the structure

Figure 81: The robot main components that influence to its energy consumption

There are at least three main factors that have the main influence on robot energy consumption, i.e. the control factor, the electrical factor and the mechanical factor. The control factor includes the trajectory path, type of robot control system and the control filter. The electrical factor includes the motor and its losses and the winding inductance. The mechanical factors include the damping coefficient, the friction torque, and the elasticity of the robot transmission (as shown in Fig. 81). By optimizing these factors, the energy consumption of the IR can be reduced.

In the 1990s, the energy consumption reduction of the robot was mainly performed by optimizing the control method of the robot [155] [156]. By implementing a proper control system, the energy consumption of the IR can be reduced up to 40% [157]. However, the modification of the robot control system can only be done by the robot manufacturers and the planning engineer as a user has limited options to implement changes in the robot control systems. Therefore in this dissertation, the analysis of the influence of the control system to robot energy consumption is not conducted.

Further discussion in this chapter is focused on the effect of the robot operating parameters and the robot's dynamics behavior on the energy consumption. The operating conditions, such as robot speed, acceleration and payload are chosen as the main parameters investigated. Based on the simulation results, these parameters have a significant influence on the robot energy consumption. It was found that the operating speed of the robot greatly contributes to the energy consumption of the robot. Also, higher speeds lead to higher power consumption since the robot motor drives need to operate the motor at a higher speed while maintaining the position and the gravitational load of the robot arms. Additionally, the higher speed tends to produce more vibration and jerks that also lead to higher energy consumption.

Furthermore, the effect of the robots dynamics behavior on the robot energy consumption is also investigated. The robot dynamics parameters such as acceleration, gravity load, robot elasticity parameters were investigated. The significant discovery is that maximum acceleration, gravity load, robot elasticity are not independent, but rather interrelated. Acceleration, while consuming energy, determines also how fast maximum velocity is reached and how long it takes to complete a trajectory. Besides this, if control or mechanical parameters are not able to stabilize oscillations, periods of constant velocity can produce a high amount of losses as well. For the axis bearing gravitational load, phases of constant velocity also consume energy. A higher acceleration shortens these periods, but at the cost of greater motor current. It also tends to excite vibrations to a great extent, producing a higher amount of energy loss. As a consequence, finding the best set of parameters entails optimization processes. Mechatronic simulation models have the potential to improve this engineering process, because interrelated phenomena are allowed and accounted for (as shown in Fig. 82). [116]

The analysis found that the operating conditions as well as the dynamics behavior of the IR have a significant influence on its energy consumption. Thus, the energy reduction of IR that are used in HS can be performed by optimizing the robot operating conditions and selecting the best possible dynamics parameters. Based on a planning engineering point of view, this energy reduction method can be easily implemented since it does not require a change of the software or hardware of the robot systems. Thus, these methods are suitable to implement in the process planning of IR.

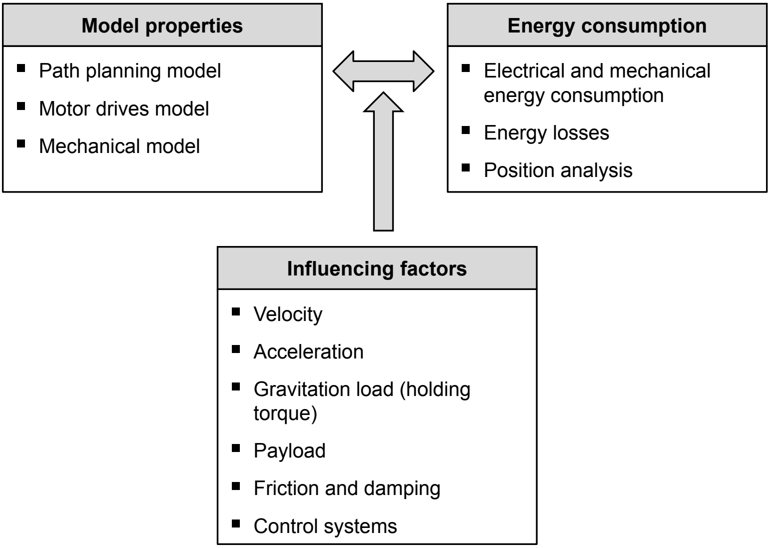

Figure 82: The correlation of the simulation model, energy consumption and the influencing factors

Furthermore, based on the investigation results that were described in the previous sections, reducing energy consumption of IR used in HS can be performed by:

- operating the IR at medium speed, in the range between 40-70% of its maximum speed,
- smoothing the robot movement to reduce/avoid jerks and vibrations, since excessive vibration and jerks consume more energy,
- avoiding a fast start-and-stop motion. It is better to move the robot slower and smoother,
- for medium and heavy robot systems, minimizing the weight of the robot gripper and its components can reduce the energy consumption. For example, this can be achieved by using lightweight materials for the robot's gripper.
- reducing the friction and increasing the damping coefficient at the robot speeds in the range between 40-70%.

A detailed discussion on the energy reduction of IR used in an automated HS and how this can be implemented in the process planning stage will be presented in Chapter 8.

8. Mechatronic Simulation Approach for Optimizing Industrial Robots' Operating Parameters

This chapter presents the study on the application of the mechatronic simulation approach for reducing the energy consumption of IR used in HS. At first, criteria that should be considered for optimizing the operating parameter of IR are described. Further, the implementation scenario of the mechatronic simulation approach as the proposed solution for optimizing the IR's operating parameters is presented. Finally, the remarks are presented at the end of this chapter.

8.1 Optimization criteria for reducing the energy consumption of industrial robots

By optimizing the operating parameters of IR, the engineer is able to reduce operation costs and increase the productivity of the manufacturing plant as well as produce better quality products. However, several criteria must be considered before optimizing the operating parameters of IR. The following section elaborates on the optimization criteria for reducing the energy consumption of IR. At first, optimization problems are presented. After that, the criteria for IR optimization in HS are explained. Based on the defined criteria, the proposed optimization method based on the mechatronic simulation approach are implemented and explained in detail.

Firstly, there are several optimization methods that can be used by engineers for reducing the energy consumption of IR. Nevertheless, two main methods to reach an optimal robot operating condition exist, and are known as the online and offline method. The online optimization is a procedure to optimize the robot parameters by "trial and error" on the real robot. Thus it needs an engineer who is working directly on the IR with a programming panel. This method is not efficient since the handling process needs to be interrupted and stopped repeatedly. On the other hand, in offline optimization, an exact simulation model of the robot is needed. The robot operating parameter will be optimized by a computer simulation and then the optimized program will be uploaded to the real robot and the results from the simulation analysis are used as the input data for an optimization task.

The following are the criteria for optimization of the robot operating parameter.

Layout constraint

The layout optimization of machines is one of the main tasks in development of an automated HS [158]. There are many requirements that should be analyzed in this task, such as material flow, machine feature and designer preference. Therefore, it needs an approach that can provide a systematic solution. In this context, a simulation approach is commonly used as the solution. Particularly for automated HS equipped with IR, a more detailed analysis is required since their working space is not exclusively in the vertical or horizontal direction but a combination of these directions. Furthermore, an IR used in handling processes always has more complex workspace constraints because it is mostly used in conjunction with another handling machine or component such as the conveyor system, the HS structure or other robots.

The handling process with two or more robots should be planned while considering their sequence, operating time and operating zone. The reason is that many robot operations have shared working zones occupied by one or two robots. Thus, their workspace should be taken into account for defining a method to reduce the energy consumption of IR.

Because of the layout constraint, an IR sometimes needs to wait or reduce its motion speed for other machine operations. To overcome this challenge, the process planning is used to define the schedule when the robot should be operated and in which operating condition it should be performed. The planning engineer needs to optimize in what condition the robot can be operated in, whether in high or low speed conditions. For example, the optimization method by changing the robot trajectory are presented in [159], while energy consumption reduction of several robots used in a HS by optimizing the robot operating schedule can be found in [151]. In these methods, the layout constraint is defined as the main criteria. However the focus of the investigation is on the cooperation among several IR.

In consequence of the robot constraint complexities, the decision to choose the optimal operating parameters of the robot is a complex task. Thus, in the development of IR model this constraint should be defined.

Productivity constraint

Energy saving is able to reduce the operation costs but should not negatively affect the productivity of the process. It means that planning engineers should consider the production rate of the system before choosing and optimizing the robot operating parameters since the productivity rate of an HS is mostly determined in the production planning stage. Therefore the optimization of robot operating parameters should be defined at the beginning of the process. At this stage, a simulation model of the robot can be very useful, to define the most optimal conditions of the robot operation.

The productivity rate of a handling process depends on the several factors:

- the complexity and size of the material that should be handled,
- operating speed of the handling machine,
- the number of the handling machine,
- the available workspace and facility design,
- required demand from the customer and
- quality of the handling machine and the sensor.

These factors show that operating speed of the machine strongly influences the productivity requirement. Therefore, the productivity constraint is the main input factor that is considered for choosing the optimal operating parameters of the robot. In this context, an optimization should be found between productivity, operating condition (e.g. speed) and the energy consumption; with the purpose of reducing the energy consumption and improving the productivity of the process.

Energy consumption constraint

Energy constraint is a newly defined constraint in the manufacturing industry, determined by the energy management staff of a company. Higher energy prices and the extended use of renewable energy sources are the main factors that lead to this constraint. The energy prices have a big influence on reducing the operation costs. Thus, industry managements typically define a specific value of the energy consumption for every process used. Each HS gets an amount of energy to use.

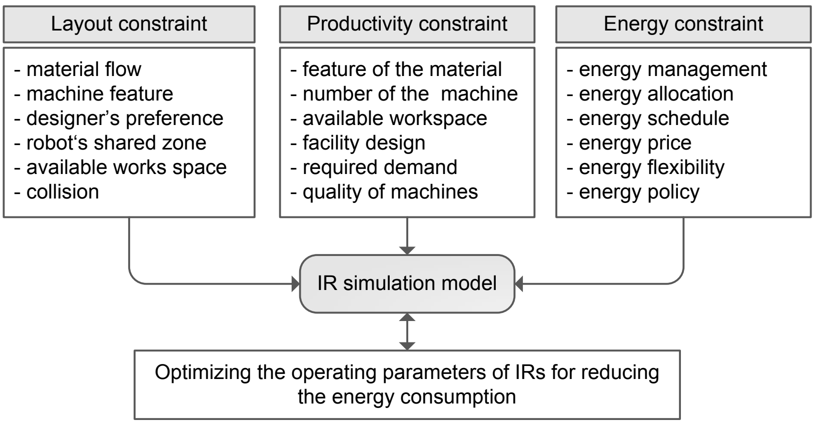

Figure 83: The main constraints for optimizing the operating parameters of IR used in automated HS

In addition, the renewable energy sources used, such as wind turbine and solar cell encourage industry management staff to define a strategy in using electrical energy since these sources of energy have a fluctuation in their supply. What this means is that the energy consumption should be maintained at a lower level for specific times or durations. Based on these reasons, IR, as a part of the system, have to fulfill energy challenges too, to keep the energy level in limit. Reduction of the energy consumption of IR as the main components of an automated HS can be used to solve the issue of inconstant energy prices and variety of energy sources. Based on the energy constraint implemented in the industry, the optimization of the operating parameter of the IR should also consider the limitation of the energy used as well as the time needed to implement it.

To summarize, the optimization criteria for reducing the energy consumption of IR are depicted in Fig. 83.

8.2 Mechatronic simulation approach for optimizing the energy consumption of industrial robots

The scenario of the proposed mechatronic simulation approach implemented in this dissertation for reducing the energy consumption of IR is presented in this section. This includes the methodology on how the approach can be integrated in process planning of HS. At the end of the section, the benefits, challenges and limitations of the approach are presented.

8.2.1 Simulation-based optimization

As mentioned before, the analysis of the energy consumption behavior of IR using an experimental investigation is impossible or difficult in many engineering cases, especially in the planning phase, when real systems have not yet been constructed. In this condition, using a simulation approach will give advantages such as reduced development time and costs. Accordingly, in the process planning of IR, using a simulation approach is advocated.

Optimization itself is a process to find the best possible solutions for a certain problem under defined objectives and constraints. So, the best solution has limited application for a specific purpose under defined constraints. The purpose is to reduce the energy consumption of IR and the constraints are layout, productivity and energy constraints, which was defined in the previous chapter. To do the optimization task, engineers need tools and methods that are appropriate for the observed problem. In this context, simulation-based optimization can be as a solution since it has the capability to analyze the correlation between the robot's parameters.

Simulation-based optimization, especially the mechatronic simulation approach, is performed by iteration. The simulation process is performed several times until the optimal conditions are found based on the defined constraints.

The workflow of the optimization process that is used in this study is illustrated in Fig. 84.

Following are the step of the optimization work flow based on Fig. 84:

1. Defining the constraint conditions (based on the real conditions) as the input parameters of the simulation model.
2. Simulating the IR model under several operating conditions for analyzing the effect of robot operating parameters on the robot energy consumption.

3. Analyzing the simulation results; investigating the influence of the robot operating parameters on the energy consumption.
4. Optimizing and classifying the input parameters of the simulation model and then defining new simulation parameters for next simulation conditions.
5. Analyzing the simulation results; investigating the influence of the robot operating parameters on the energy consumption.

   …

   Iteration of step no. 3 and 4 until the optimal conditions based on the defined constraints are met.

   …
6. Concluding and classifying the influence of the robot operating parameters on the energy consumption based on the simulation results.

Using the presented optimization process, the optimal operating conditions for an IR can be obtained, which is decided after considering the defined constraints.

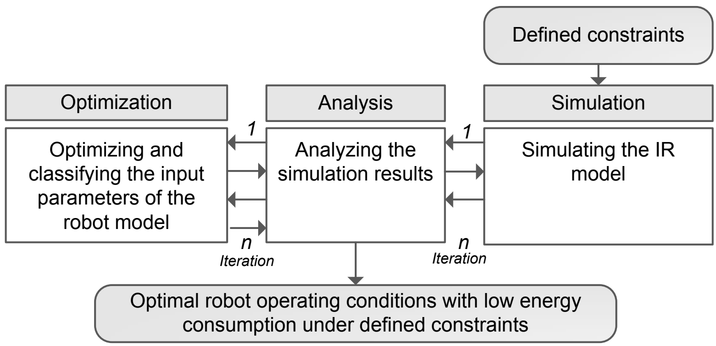

Figure 84: The simulation-based optimization process for defining energy-optimal IR operating parameters

8.2.2 Implementation scenario

The implementation of the mechatronic simulation approach in process planning of IR in the real condition is discussed in this sub-section.

In the process planning phase, the main purpose of the developed approach is to analyze the energy consumption, kinematics and dynamics behavior of the HS machine. Then, using this behavior data, the optimal strategy to reduce the energy consumption as well as to improve the performance of the machine is decided. Following this, an HS, which is commonly consisting of several machines, that operates at optimum energy levels, can be developed. The application of the proposed approach in the process planning of an HS can be seen in Fig. 85.

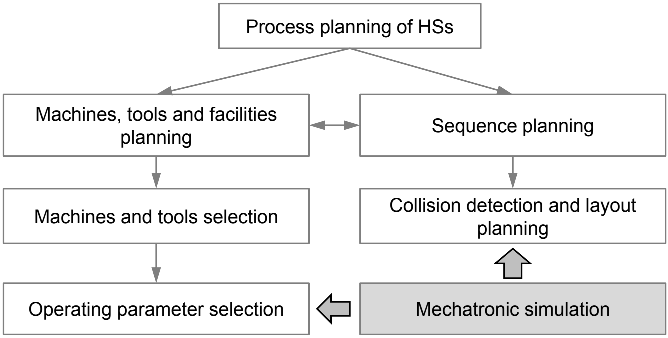

Figure 85: The application of the mechatronic simulation in the process planning of a HS

As shown in Fig. 85, the process planning task of an HS is divided into two main tasks, i.e. sequence and facilities planning. Sequence planning objectives are to define and optimize the process sequence of the material flow to improve the productivity and effectivity of the systems. In sequence planning, the task includes analyzing the collision detection and layout planning, which is used to ensure that the HS is free from collisions and designed to use the workplace efficiently.

Furthermore, the other task in process planning involves defining and optimizing the handling facilities, including machines, tools and the peripheral systems. Then, the engineers select operating parameters for every machine and tool. In this context, the mechatronic simulation can be used for analyzing and optimizing the operating parameters of the machines and support collisions and layout analysis. The developed approach can not only be used to determine the energy-optimal operating condition of HS machines, but is also able to reduce the time for developing the HS since the commissioning and optimizing process can be performed using the simulation models.

Fig. 86 depicts more specifically the IR process planning as a detailed implementation scenario of the developed simulation approach. The first step is to collect the information of the robot process productivity requirement and the robot environment conditions such as the robot dimension, layout and the available working space. Then, the collected data is interpreted to define the input parameters for the robot simulation model. Based on the input parameters, e.g. speed, acceleration and positions, the simulation is executed.

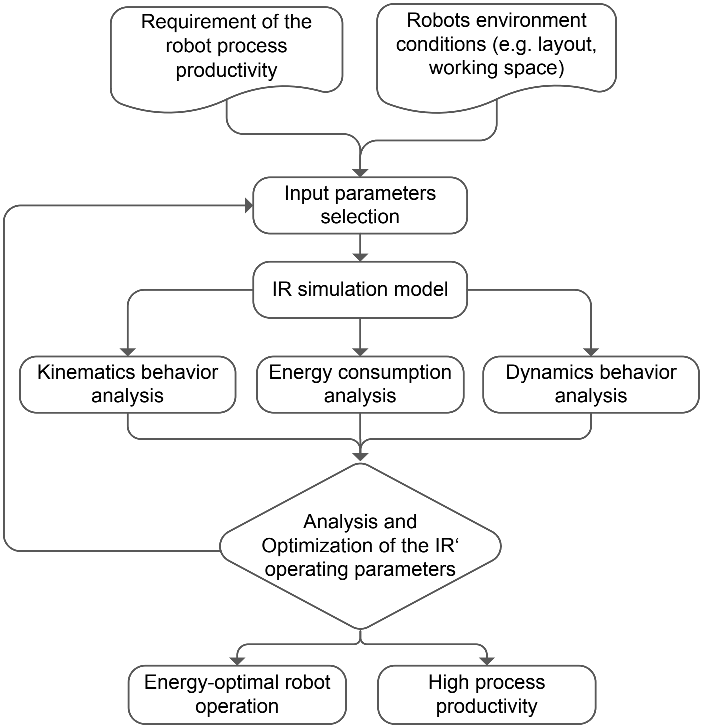

Figure 86: The implementation schema of the mechatronic simulation approach for reducing the energy consumption and improving the productivity of IR

Secondly, the simulation results from the IR model are used to analyze the energy consumption, kinematics and dynamics behavior of the robot. The energy profile and its behavior are then analyzed, especially their correlation with the operating conditions of the robot. Furthermore, the analysis of the influence of the dynamics behavior of the robot on the energy consumption is also conducted. This is used to ensure that the robot not only operates at optimal energy- levels but also at its best possible performance, which in this context is represented by its dynamics behavior.

From the analysis of the kinematics, energy and dynamics behavior of the robot, the strategy to operate the robot at low energy consumption is defined with consideration of the process productivity of the robot. Then, the optimization process is performed repeatedly with the simulation of the robot until the optimum solutions under defined requirements and constraints are obtained. The process optimization is performed based on the process that was presented in the previous sub-section (see Fig. 84).

8.2.3 Benefits and limitations of the approach

Several benefits from the proposed approach for the process planning of HS are described in this sub-section. The list of the benefits and the limitations of the approach are described as follows.

Benefits from the proposed approach

- Able to reduce the energy consumption of IR by optimizing their operating parameters since the energy consumption of the robots can be analyzed based on their real operating conditions. Therefore, the robots are operated at their optimal operating speed, payload and their optimum energy level. Also, the reductions of the energy consumption will directly reduce the energy cost which indirectly helps industries to reduce their CO_2 emissions.
- The proposed approach can help planning engineers to define the strategies for facing the new challenge of energy source flexibility. The energy prediction of the handling machines can help engineers better predict the energy consumption of the systems during their operation.
- Improving performance of the IR by choosing the optimal parameters, therefore avoiding excessive vibrations and jerks. The proposed simulation approach can also be used for analyzing the robot dynamics behavior. Based on this, planning engineers can select the appropriate parameters that produce minimal jerks and vibrations.
- Able to be used for collision detection and robot motion analysis. These kinds of analyses will help planning engineers to develop a high performance and collision free HS.

Limitation of the approach

Although there are many benefits of the mechatronic simulations approach for the process planning of HS. The developed approach also has limitations, e.g.:

- The proposed approach is designed for analyzing a single or few machines. The energy analysis of a complete HS, which is mostly consisting of several machines is difficult to be performed in a single simulation environment. The whole energy consumption analysis of an HS is performed by summing the energy consumption of every HS machine and component.
- Detailed mechatronic model will help engineers to analyze the influences of several sets of parameters of the robot regarding its energy consumption. However, the initial effort to develop a modular model is great since engineers need to develop an IR model at a high level of accuracy.
- Because the detailed mechanical, electrical and control parameters of IR are mostly withheld, the real systems can only be approximated as far as the assumptions made are valid. The experimental validation involves mostly

additional effort and costs to ensure that the approximations and assumptions are valid.

However, the developed model itself is coherent. Its behavior with regard to energy consumption and accuracy can be explained by investigation of internal quantities, such as currents, joint torques and ideal position errors. Their accessibility is a major advantage of simulation.

8.3 Summary and remarks of the developed approach

In terms of IR, the energy consumption prediction will help engineers to define an appropriate strategy for reducing the energy consumption. For instance the energy consumption of IR in an automated HS will consume about 8-50%, depending on the type of HS. This means that an appropriate strategy for reducing the energy consumption of IR will give a significant reduction on energy costs and CO_2 emissions.

The energy reduction of IR can be achieved by optimizing the operating conditions of the robot by adjusting their sets of parameters. The main drawback of this method is that no energy data can be used as the basis for the optimization. The energy data given in the machine's manual proves to be unreliable since the energy consumption of the robots strongly depends on the environment where they are utilized, which can vary from one to other applications. In this research, the energy model of IR is developed to solve this drawback, which is to give exact energy consumption data of the robot during actual operation conditions.

The chapter presents several constraints that should be considered when implementing the proposed energy reduction method, such as layout, productivity and energy consumption. The layout constraint, for example, should be well defined in the developed IR's simulation model, since it will influence the collision and the operating speed of the robot. While the productivity requirement will affect the robot's process planning, especially in the decision to choose the optimum operating speeds, not only based on its energy consumption but also on its productivity. The energy consumption constraint, also limits the robot's operation time and operating condition. The effect of energy prices and the flexibility of the energy source are the main reasons to consider this constraint in the process planning process.

Based on the analysis that was described in Chapters 6 and 7, the application of the proposed solution method, which is based on the mechatronic simulation approach is effectively used for the purpose of energy optimization. Therefore, it is suggested for use in the process planning of IR as part of an automated HS for reducing its energy consumption. This chapter also describes a step-by-step approach for implementing the mechatronic simulation approach in the real HS.

Based on the case study analysis many advantages can be gained by implementing this method. However, there are limitations and challenges that remain, such as the lack of integration with common simulation tools that are available commercially, which are mostly based on DES. Therefore, approaches that can solve these issues are suggested for further research.

9. Summary and Future Work

In the process planning of an automated handling system (HS), there are many factors that must be considered, such as productivity requirements, facility layout design and the operating conditions of machines. Therefore, the process is complex, time-consuming and cost-intensive. Furthermore, conventional process planning approaches do not involve energy consumption optimization, especially for complex handling machines such as industrial robots (IR). Thus, many opportunities are still available in order to reduce the energy consumption of HS.

In the HS for mechatronic and automotive industries, IR consume about 8-50% of total energy consumption, depending on their application. For instance, IR consume about 50% of energy in the automotive body shop. Thus, reducing and optimizing the energy consumption of IR will lead directly to a reduction of the energy costs, as well as lower CO_2 emissions.

In addition, an observable trend in manufacturing research is focused on the development of the digital factory. As a consequence of this, a simulation model of IR that is capable for analyzing their energy profiles at several operating conditions and applicable for several robot types is expected. Furthermore, the simulation model should not only focus on the kinematics simulation of the robot but also have the capability to simulate the robot's internal components (e.g. mechanical, control and electrical systems). In order to address these requirements, a mechatronic simulation approach that is used to develop a modular model of IR as part of HS is proposed. This approach is based on multi-domain and object-oriented simulation paradigm, which is designed for the process planning of IR, in particular for optimizing their operating conditions.

The IR model is developed using the concept of modularity, which models the robot's components such that they can be used for any robot model by changing their input parameters. Within the scope of this research, the robot model is divided into four main components, i.e. mechanical structure, control system, motor drive system as well as energy and position module. Also, the robot model is developed to accommodate actual operating conditions of the HS such as its productivity requirements and facility layout constraints.

Using the object-oriented and multi-domain modeling paradigm, the developed model can analyze the energy consumption as well as kinematics and dynamics behavior of IR. The energy consumption analysis is performed based on the simulation results of the electrical, mechanical and dynamics behavior of the robot. Therefore, an energy profile of IR at several operating conditions can be monitored and visualized together with its kinematics and dynamics behavior.

Verification and experimental validation is performed in order to evaluate and improve the accuracy of the developed model. Investigations using the Motoman MH5L robot, a part of a work cell, show that the value of deviation of the power consumption between simulation and measurement results is less than 6%, which can be explained by the limitation of the simulation tool for modeling the IR's supporting components such as robot control unit, PC and monitor. Nevertheless, the energy consumption trend from simulation results is similar to the experimental results. At the beginning of the robot's motion, power consumption and current are relatively high due to the acceleration of the motor drives. Besides this, operating parameters, such as velocity, payload, as well as the trajectory of IR have a significant impact on their energy consumption.

By using the approach, planning engineers are able to optimize the energy consumption and kinematics behavior of IR as part of HS without performing an experimental investigation. This is very useful for engineers for designing or changing the handling sequence when new requirements of the production process are given, e.g. when HS need to handle a new product variant. Furthermore, this allows engineers to define an appropriate strategy in order to minimize the energy consumption of IR.

Based on the simulation and experimental investigation, there are several methods that can be implemented to reduce the energy consumption of IR that are used in HS:

- smoothing IR motion for reducing excessive energy needed to accelerate the robot motion,
- operating IR at medium speeds (about 40-70% of the maximum speed), since higher speeds lead to higher energy consumption,
- reducing the weight of the IR' payload and tool systems, which reduces the required torque.

Moreover, the kinematics analysis of the robot shows that the developed simulation model can be used for the functions of analyzing the robot motion sequence and collision detection. This includes calculating the required duration for the robot movement. Furthermore, an analysis of the dynamics has proven that the robot model can conveniently be used for investigating the robot's torque, speed response and accuracy.

In terms of process optimization, the robot speed and acceleration has the major influence on robot energy consumption. By choosing optimum speeds, the energy consumption of the IR can be reduced significantly. From this investigation, it was found that by operating the robot at 50% of its maximum speed, a reduction in energy consumption of about 20% can be achieved relative to a robot operating at the standard maximum speed. Nevertheless, energy consumption is not determined by speed alone, but is influenced by a host of other factors, including the robot control system, robot friction and damping, as well as the robot standstill position.

Furthermore, the developed approach has the advantage that it can be implemented on any handling machine and is not limited to IR. Other investigations not described in this dissertation or outside the scope of this work show that the mechatronic simulation approach can be used for analyzing the energy consumption of a conveyor system and a pick-and-place machine. Therefore, based on the research results, the application of the developed approach using a multi-domain modeling simulation tool, can serve as a promising method for the energy consumption, kinematics and dynamics behavior analysis of HS machines.

Nevertheless, based on the case study analysis, challenges still remain for the successful implementation of the proposed approach. There is a lack of integration with common simulation tools that are available commercially, which are mostly based on kinematics and discrete event simulation. Therefore, in order to produce better results, the issue of integration should be addressed in future investigations within this field. Finally, to further reduce the energy consumption of HS significantly, the analyzing and optimizing of the operating conditions of the peripheral components, such as the compressor and transport machines, should also be explored in future research.

10. Zusammenfassung

Bei der Prozessplanung eines automatisierten Handhabungssystems (HS) sind mehrere Einflussfaktoren zu berücksichtigen, unter anderem Anforderungen an die Produktivität, prozessbedingte Einschränkungen, Layout und Betriebszustand der Maschinen. Dies führt zu einer komplexen, zeitaufwändigen und kostenintensiven Prozessplanung. Zudem erfolgt im Rahmen der konventionellen Prozessplanungsansätze keine Optimierung des Energieverbrauchs, insbesondere bei der Prozessplanung von komplexen Maschinen wie Industrieroboter (IR). Infolgedessen bestehen noch viele Ansatzpunkte um den Energieverbrauch von HS zu reduzieren.

In HS der Automobilindustrie beträgt der Anteil von IR am gesamten Energieverbrauch etwa 8-50% (in Abhängigkeit von der Anwendung). Zum Beispiel liegt der Anteil von IR am gesamten Energieverbrauch im Karosseriebau bei ca. 50%. Damit führt die Reduzierung und Optimierung des Energieverbrauchs von IR direkt zur Reduzierung der Energie kosten sowie zu geringeren CO_2 Emissionen.

Zusätzlich ist ein Trend im Bereich der Fertigung zu beobachten, dass Forschungsschwerpunkte zunehmend auf Entwicklungsleistungen für die Digitale Fabrik gelegt werden. Als Konsequenz werden Simulationsmodelle von IR entwickelt, welche die Fähigkeit besitzen, die Energieprofile verschiedener Betriebszustände zu analysieren. Diese Modelle sollen für verschiedene Robotertypen einsetzbar sein. Darüber hinaus kann das Simulationsmodell nicht nur den kinematischen Vorgang des Roboters simulieren, sondern auch eine Simulation der Komponenten des Roboters ermöglichen (z.B. der mechanischen und elektrischen Systeme oder der Steuerungssysteme). Um diesen Anforderungen zu begegnen, wurde ein Ansatz der mechatronischen Simulation entwickelt, welcher beim Entwurf eines modularen Modells für IR als Bestandteil von HS Anwendung findet. Diese Vorgehensweise basiert auf dem objektorientierten Multi-Domain-Simulationsansatz, welcher zur Prozessplanung von IR, insbesondere zur Optimierung ihrer Betriebszustände, entwickelt worden ist.

Für die Entwicklung des IR-Modells wird das Konzept der Modularität angewendet, wodurch die Roboterkomponenten so modelliert werden, dass diese - durch Änderung der Inputparameter - für jegliches Robotermodell eingesetzt werden können. Im Rahmen dieser Forschungsarbeit wurde das Robotermodell in vier Hauptkomponenten untergliedert, den mechanischen Aufbau, das Steuerungssystem, das Antriebssystem sowie das Energiemodul. Darüber hinaus basiert die Entwicklung des Roboters auf tatsächlichen Betriebsbedingungen des HS, z.B. Produktivitätsanforderungen und Layout-Beschränkungen des Arbeitsbereiches.

Der Lösungsansatz mit Multi-Domain- und objektorientierter Modellierung wird sowohl zur Analyse des Energieverbrauchs als auch des kinematischen und dynamischen Verhaltens der IR entwickelt. Die Analyse des Energieverbrauchs erfolgt auf Grundlage der Simulationsergebnisse des elektrischen, mechanischen und dynamischen Verhaltens des Roboters. Dadurch kann das Energieprofil von IR in verschiedenen Betriebszuständen mitsamt ihres kinematischen und dynamischen Verhaltens überwacht und visualisiert werden.

Verifikation und experimentelle Validierung dienen dazu, die Genauigkeit des entwickelten Modells zu bewerten und zu verbessern. Untersuchungen mit Hilfe des Roboters Motoman MH5L, welcher ein Bestandteil einer Fertigungszelle ist, zeigen, dass die Abweichung des Energieverbrauchs zwischen den Simulationsergebnissen und den Messergebnissen nur ca. sechs Prozent beträgt. Dies ist auf die beschränkte Möglichkeit des Simulationstools, die periphere Komponenten des IR, z.B. Robotersteuereinheit, PC und Monitor zu modellieren, zurückzuführen. Trotzdem ist der Verlauf des Energieverbrauchs ähnlich. Am Anfang der Roboterbewegung ist der Energieverbrauch aufgrund der Beschleunigung des Motorantriebes relativ hoch. Zudem wirken sich Betriebsparameter, z.B. Geschwindigkeit, Traglast und Pfad der IR, signifikant auf den Energieverbrauch aus.

Unter Anwendung dieses Ansatzes sind Planungsingenieure in der Lage, den Energieverbrauch und das kinematische Verhalten der IR zu optimieren, ohne experimentelle Versuche durchführen zu müssen. Besonders nützlich ist der Ansatz für Ingenieure bei der Erstellung und Änderung von Handling-Vorgängen. Dies geschieht bei neuen Anforderungen des Produktionsprozesses, z.B. wenn eine neue Produktvariante eingeführt wird. Zudem bietet der Ansatz Anwendern eine geeignete Strategie, den Energieverbrauch der IR zu minimieren. Auf Grundlage der Ergebnisse der Simulation und der Messung gibt es verschiedene Methoden, um der Energieverbrauch der IR zu minimieren:

- Eine Glättung der Bewegung des IR, um den übermäßigen Energieverbrauch für die Beschleunigung zu reduzieren.
- Die Reduzierung der Geschwindigkeit auf mittlere Werte (40-70% der maximalen Geschwindigkeit), da höhere Geschwindigkeiten zu einem höheren Energieverbrauch führen.
- Die Minimierung der Nutzlast und des Werkzeuggewichtes, um das erforderliche Drehmoment zu reduzieren.

Die kinematische Analyse des Roboters zeigt, dass die entwickelte Simulation die Funktionen der Analyse des Bewegungsablaufs des Roboters und der Kollisionserkennung erfüllen kann. Zudem kann die Dauer der Roboterbewegung berechnet werden. Zusätzlich zeigt die dynamische Analyse, dass das Robotermodell das Drehmoment und die Genauigkeit des Roboters analysieren kann.

In Bezug auf die Prozessoptimierung haben die Robotergeschwindigkeit und Beschleunigung den größten Einfluss auf den Energieverbrauch. Daraus folgt, dass die Einstellung optimaler Geschwindigkeiten den Energieverbrauch der IR maßgeblich reduzieren kann. Die Erkenntnisse aus den Versuchen zeigen, dass eine

Reduzierung der Robotergeschwindigkeit auf 50% zu einer Reduzierung des Energieverbrauchs um 20% führt. Der Energieverbrauch ist jedoch nicht nur von der Geschwindigkeit abhängig, sondern wird auch von der Roboterposition, der Reibung und Dämpfung sowie der Steuerung beeinflusst.

Des Weiteren hat der vorgestellte Ansatz den Vorteil, dass er nicht nur für IR geeignet ist, sondern für jegliche Handhabungsmaschinen implementierbar ist. Weitere Untersuchungen über den Rahmen dieser Dissertation hinaus zeigen, dass der Ansatz der mechatronischen Simulation auch auf ein Fördersystem und einen Bestückungsautomat übertragbar ist. Auf den Forschungsergebnissen beruhend kann der Ansatz mit Hilfe eines Multi-Domain Simulationswerkzeugs daher als erfolgversprechender Ansatz zur Analyse des Energieverbrauchs und des kinematischen und dynamischen Verhaltens von HS bezeichnet werden.

Zum Schluss zeigt die Fallstudienanalyse, dass Herausforderungen noch zu beheben sind, um den Ansatz erfolgreich zu implementieren. Zum einen ergibt sich eine fehlende Integration mit gängigen Werkzeugen, welche hauptsächlich auf DES basieren. Bessere Ergebnisse können daher nur produziert werden, wenn weitere Untersuchungen sich mit der Fragestellung der Integration beschäftigen. Des Weiteren kann der Energieverbrauch der IR noch weiter reduziert werden, indem die Betriebszustände der Peripherie-Komponenten, wie des Kompressors und der Materialflusssysteme, analysiert und optimiert werden.

11. List of Abbreviations and Nomenclature

Abbreviations

BLAC .... Brushless Alternating Current
BLDC .... Brushless Direct Current
CAD .... Computer Aided Design
CAE .... Computer Aided Engineering
CFD .... Computational Fluid Dynamic
CO_2 .... Carbon Dioxide
CPU .... Central Processing Unit
CTC .... Computed-Torque Controllers
DES .... Discrete Event Simulation
DC .... Direct Current
DH .... Denavit-Hartenberg
EN .... Europäischen Normen
EMF .... Electromotive Force
FEA .... Finite Element Analysis
FMS .... Flexible Manufacturing Systems
HS .... Handling System
IEEE .... Institute of Electrical and Electronics Engineers
IFR .... International Federation of Robotics
IR .... Industrial Robots
ISO .... International Organization for Standardization
MES .... Manufacturing Execution Systems
MTM .... Method Energy Measurement
MSL .... Modelica® Standard Library
NC .... Numerical Control
PC .... Personal Computer
PFA .... Product Family Architecture
PI .... Proportional-Integral
PID .... Proportional-Integral-Derivative
PRP .... Delmia Process Planning
PS .... Production Systems
PMSM .... Permanent Magnet Synchronous Motor
PTP .... Point-To-Point

PV................Photovoltaics
REFA...........Reichsausschuß für Arbeitszeitermittlung
RFLP ....Requirements, Functional, Logical, Physical
RMS ....Reconfigurable Manufacturing Systems
SCS ....The Society for Modeling & Simulation
TCP ....Tool Center Point
UCM ....Universal Contacting Module
VDI ....Verein Deutscher Ingenieure
3D................3 Dimension

Nomenclature

Roman symbols

c_o	Spring coefficient	[N.m/rad]
d_o	Damping coefficient	[N.m.s/rad]
F_f	Instantaneous friction force	[N]
F_v	Viscous friction force	[N]
f_o	Viscous coefficient	[N.m.s/rad]
G	Conductance	[S]
I	Inertia parameter of robots's arm	[kg.m^2]
i	Current	[A]
J	Moment of inertia motor	[kg.m^2]
k	Motor constant	[-]
L	Inductance	[H]
m	Mass	[kg]
m_{tot}	Robot's mass total	[kg]
P	Power	[W]
P_{mech}	Mechanical power	[W]
P_{el}	Electrical power	[W]
p	Number of pole pair	[-]
p_{loss}	Power losses	[W]
p_c	Core losses	[W]
p_f	Friction losses	[W]
p_r	Rotor and rotor losses	[W]
p_{ref}	Losses reference	[W]

p_s	Stray load losses	[W]
R	Resistance	[Ω]
r_H	Hysteresis ratio	[-]
U	Signal voltage	[V]
V	Voltage	[V]
V_{tot}	Robot's volume in total	[m^3]
v	Speed	[m/s]
W	Energy consumption	[J]

Greek symbols

α_{ref}	Reference temperature	[K]
ρ	Density	[kg/m^3]
φ	Power angle	[rad]
τ	Torque	[N.m]
ω	Angular speed	[rad/rad]
$\dot{\omega}$	Angular acceleration	[rad/s^2]
η_{el}	Electrical coefficient	[-]
η_{mec}	Mechanical coefficient	[-]

12. List of Papers

The following lists the published papers by the author that are related to the dissertation. Similar contents of this dissertation can also be found in these papers, especially in papers no. 1-7.

1) **Paryanto**; Brossog, M.; Bornschlegl, M.; Franke, J.: Reducing the energy consumption of industrial robots in manufacturing systems. In: *The International Journal of Advanced Manufacturing Technology*, Vol. 78, Issues 5-8 (2015), pp. 1315-1328.

   DOI: http://dx.doi.org/10.1007/s00170-014-6737-z

2) **Paryanto**; Brossog, M.; Kohl, J.; Merhof, J.; Spreng, S.; Franke, J.: Energy consumption and dynamic behavior analysis of a six-axis industrial robot in an assembly system. In: *Procedia CIRP*, Vol. 23 (2014), pp. 131-136.

   DOI: http://dx.doi.org/10.1016/j.procir.2014.10.091

3) **Paryanto**; Merhof, J.; Brossog, M.; Fischer, C.: An integrated simulation approach to the development of assembly system components. In: *Advanced Materials Research*, Vol. 769 (2013), pp. 19-26.

   DOI: http://dx.doi.org/10.4028/www.scientific.net/AMR.769.19

4) **Paryanto**; Brossog, M., Merhof, J.; Franke, J.: Mechatronic behavior analysis of a customized manufacturing cell. In: *Lecture Notes in Production Engineering*, (2014), pp. 389-399.

   DOI: http://dx.doi.org/10.1007/978-3-319-04271-8_33

5) **Paryanto**; Hetzner, A; Franke, J.: A dynamic model of industrial robots for energy examination purpose. In: *Applied Mechanics and Materials*, Vol. 805 (2015), pp. 223-230.

   DOI: http://dx.doi.org/10.4028/www.scientific.net/AMM.805.223

6) **Paryanto**; Brossog, M.; Roppelt, M.; Franke, J.: A model-based approach for the energy monitoring of handling machines. In: *Applied Mechanics and Materials*, Vol. 856 (2017), pp 57-63.

   DOI: http://dx.doi.org/10.4028/www.scientific.net/AMM.856.57

7) Bornschlegl, M.; **Paryanto**; Spahr M.; Kreitlein S.; Bregulla M.; Franke J.: Energy planning of manufacturing systems with methods-energy measurement (MEM) and multi-domain simulation approach. In: *Applied Mechanics and Materials*, Vol. 655 (2014), pp. 53-59.

   DOI: http://dx.doi.org/10.4028/www.scientific.net/AMM.655.53

8) Meinel, D.; **Paryanto**; Franke, J.: Chances of the application of multi-domain simulation tools in the field of train system engineering, In: *Flexible Automation & Intelligent Manufacturing* (2014), pp. 893-900, DEStech Publications, Inc.

9) Hauf, D.; Meike, D.; **Paryanto**; Franke, J.: Energy consumption modeling within the virtual commissioning tool chain, In: *11th IEEE International Conference on Automation Science and Engineering* (CASE), (2015), pp. 1357-1362.

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10) Meinel, D.; **Paryanto**; Franke, J.: Methodology towards computer-aided testing of complex mechatronic systems, In: *Procedia CIRP*, Vol. 41 (2016), pp. 247-251.

    DOI: http://dx.doi.org/10.1016/j.procir.2015.12.121

11) Zhang X., Scholz M., **Paryanto**, Franke J.: Adaptive optimal multiple object tracking based on global cameras for a decentralized autonomous transport system. In: *Applied Mechanics and Materials*, Vol. 840 (2016), pp 1-7.

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In papers no. 1-6, Paryanto is the main contributing author, while the co-authors Matthias Brossog, Jochen Merhof, Christian Fischer, Johannes Kohl, Simon Spreng, Alexander Hetzner and Manuel Roppelt are persons involved in the proofreading of the paper draft and assisted through discussions. Prof. Jörg Franke is the person that supervises the research work.

In paper no. 7, Paryanto describes the IR simulation model and proofread the paper draft. In paper no. 8-11, Paryanto contributes to the proof reading and assisted in discussions.

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