NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY "POLITEHNICA" BUCHAREST
Faculty of Industrial Engineering and Robotics
Department of Robots and Production Systems

Florin Ghe. ENACHE

Generalized model for Production Process Analysis

- PhD thesis abstract *

PhD supervisor,
Prof.univ.dr.eng. Stefan VELICU (UNSTPB)

- 2023 -

National University of Science and Technology "Politehnica" Bucharest
Faculty of Industrial Engineering and Robotics
Department of Robots and Production Systems

WORD BEFORE

WORD BEFORE

The research and development presented in this doctoral thesis represent the result of a passionate and dedicated journey into the field of production process analysis and the impact of robotic cells on them. This doctoral program consisted of a series of intellectual challenges, valuable discoveries, and the improvement of production processes through the application of state-of-the-art technology.

As a researcher, I was committed to exploring the new frontiers of knowledge and seeking innovative solutions to today's industry challenges. My doctoral program involved rigorous preparation, passing examinations, and presenting relevant scientific reports, all of which were crucial steps in developing my scientific and academic competencies.

One of the keys to this endeavor was the in-depth study and identification of essential aspects of production processes that could benefit from the implementation of robotic cells. I explored the advantages offered by advanced technology, its impact on operational efficiency, and the prospects for improving the quality of end products.

During this program, I had the opportunity to collaborate with specialists from various fields in an environment conducive to the exchange of ideas and experiences. We shared knowledge and expertise, collectively analyzed the challenges and opportunities posed by robotic cells in the context of production process analysis.

The result of these efforts was the creation and publication of scientific papers that contributed to the advancement of the field and the dissemination of knowledge to the scientific community.
These papers formed the foundation of this doctoral thesis, in which I developed a "Generalized Model for the Analysis of Production Processes," thus providing a coherent and comprehensive framework for understanding and optimizing industrial processes.

In conclusion, I would like to express my gratitude to all those who supported me on this "journey," starting with Professor Stefan Velicu, PhD, for his unwavering patience, dedication, and kindness in providing answers to my questions, valuable advice, and wise guidance. Under his guidance, I gained not only academic knowledge but also essential skills in critical thinking and research problem-solving, benefiting from dedicated and passionate mentorship. Thank you, Professor!

I also extend my thanks to Professor Constantin Dogariu, PhD, for the encouragement and advice provided during the defense of scientific reports.

I continue by thanking my family for relieving me of other responsibilities to focus on study and research, and then to trusted colleagues to whom I bow in gratitude.

With confidence in the contribution of this doctoral thesis to the scientific and technological program, I sincerely address these words to all those interested in the field of production process analysis and the impact of robotic cells on it.

I hope that this work will inspire and generate new ideas and perspectives for the future of the manufacturing industry and serve as a source of information and knowledge for all those passionate about progress and innovation.

With gratitude,
Florin Enache

INTRODUCTION

In the dynamic context of the modern industry, enhancing the performance of production processes is a key objective for companies in various fields of activity. Improving efficiency, reducing costs, optimizing product quality, and maximizing resource utilization have become critical factors in achieving success in the market. Consequently, research in the field of improving production process performance has become increasingly relevant and necessary. The aim of this work is to identify and apply the most efficient methods and techniques to optimize manufacturing workflows and increase efficiency within production processes.

The thesis addresses aspects of production processes, such as emerging technologies, automation, manufacturing workflow optimization, supply chain management, production planning, and scheduling. The primary objective of all this research is to identify and develop innovative methods, techniques, and solutions to enhance production process performance and gain a competitive advantage.

Currently, there is a wide range of research in the field, conducted in both academic and industrial settings, relying on solid theoretical foundations and practical applications specific to each industrial sector. Researchers explore a multitude of advanced technologies, such as artificial intelligence, data analysis, collaborative robots, the Internet of Things (IoT), and additive manufacturing, to improve performance and bring innovation to manufacturing processes.

Analyzing the current state of research on production process performance is necessary to understand current development directions, emerging trends, and challenges faced, providing a comprehensive perspective on recent performance achievements and field results. This contributes to the development and implementation of efficient practices in the industry.

Through this work, we aim to explore and thoroughly analyze the results of recent research in the field of production process performance improvement, examining innovative methods and techniques and evaluating their impact on industrial performance, while identifying possible future development directions. The purpose of this work is to contribute to the understanding and promotion of advanced and efficient practices in the field of production.

This analysis of the current state of research on improving production process performance and the obtained results have the potential to inspire and guide companies, researchers, and decision-makers in making the best strategic decisions regarding industrial performance improvement. By consolidating existing knowledge and promoting innovation, this work contributes to the development of a more competitive, efficient, and sustainable industry.

CHAPTER 1 provides an overview of the current state of research on improving production process performance. It analyzes modern manufacturing technologies and highlights the importance of Agile principles in the context of production process optimization. It also explores the concepts of system identification and process modeling using Agile, providing an overview of process categories and types of production. The chapter continues with detailed discussions of the Lean concept and Design Thinking. These methods not only enable waste reduction and cost savings but also stimulate innovation and collaboration within the production team.

CHAPTER 2 presents a theoretical development of issues related to production process improvement. Key elements of production processes, their classification, and their importance in the context of optimization are analyzed. The chapter also presents methods for improving production processes, including approaches such as Lean manufacturing and modern human resource management. This chapter provides insight into holistic process performance and modern production monitoring methods. It also focuses on approaches and methods for improving production processes. Lean manufacturing principles are developed in detail, highlighting how they can lead to increased efficiency through waste reduction and resource optimization.

Modern human resource management is also discussed, emphasizing the importance of adapting human resource strategies to the requirements of new generations.

CHAPTER 3 focuses on the mathematical modeling of production process optimization. A mathematical approach to the analysis of production workflows is developed, and the concept of multicriteria optimization is explored. By using analytical methods and modeling techniques, the chapter makes significant contributions to identifying optimal solutions for improving production processes. Multicriteria optimization is presented as a powerful approach to identify balanced and efficient solutions for process improvement.

CHAPTER 4 highlights the potential for improving production processes through simulation. Various simulation models used in the industry are discussed, and case studies on optimization through simulation and experimental validation are presented. This chapter makes a significant contribution to the efficiency and improvement of production processes. It also provides practical contributions by implementing simulation to assess the impact of production changes.

Chapter 5 presents the experimental research conducted to assess the impact of automation through robotics in production processes. It validates the proposed theoretical model for identifying necessary changes and designing the manufacturing flow, implementing robotic operations, and monitoring production flows. Through the analysis of the obtained results, the chapter provides insight into performance improvements following the implementation of robotic solutions.

In Chapter 6, the focus is on the use of multicriteria equations in the analysis and optimization of production processes. An analytical approach is developed to evaluate the performance and efficiency of processes, taking into account multiple criteria that influence the outcomes. The chapter reviews personal contributions made in theoretical and experimental research, the advantages of using these innovative techniques, future development paths, and a list of the four scientific articles published and in the process of publication. This chapter contributes to a deeper understanding of production processes through multicriteria evaluation, providing concrete data and research results.

The bibliography of this thesis includes a total of 127 technical and scientific works and web page links that were accessed during the period from 2018 to 2023.

Therefore, this work represents a comprehensive investigation into production processes and optimization methods, making significant contributions to the field of performance improvement and efficiency enhancement in the industry.

CHAPTER 1 - STATE OF THE ART OF RESEARCH ON INCREASING THE PERFORMANCE OF PRODUCTION PROCESSES

1.1. Introduction

Modern manufacturing technologies are the set of methods, techniques and equipment usedfor the efficient and optimised production of goods.

Modern manufacturing technologies have an impact on the efficiency, quality, flexibility and sustainability of production processes, helping to reduce costs, increase productivity, improve product quality and offer customised and adaptable solutions to marketrequirements.

1.2. Identification of production systems

1.2.1. Production system - Components of production flows

The process of producing material products involves a set of raw materials and materials, also called objects of labour, taken from nature or representing the result of other activities.

The production system consists of:

- the actual manufacture of industrial material goods, an activity carried out through the industrial production process;
- research and testing of new products, which are directly linked to manufacturing.

The production process is the totality of the natural and man-made components, labour and production relations that contribute to the production of the products or the execution of the works and services that constitute the object of the enterprise's activity.

Within the production system,depending on the way in which humans intervene, the following types of processes can be distinguished:

1.2.2. Types of production andorganisation inmanufacturing

- Production and auxiliary processes - a look at the transformation of raw materials into finished products and secondary services;
- Serving/servicing production processes - the contribution of ancillary departments to the running of core and production processes;

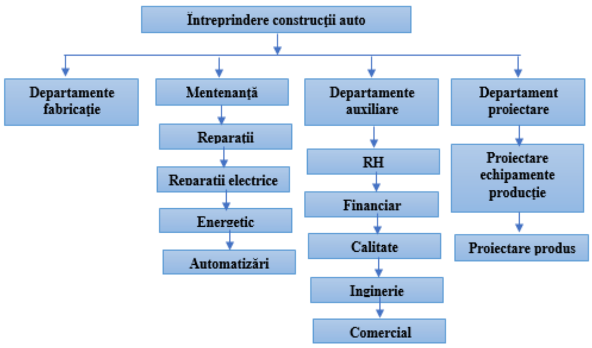


Fig.1.5 - Representation of Technological Production

1.2.3. Types of flows and concepts in production organisation:

- technological organisational structure (see Fig. 1.5) - arrangement of workplaces in homogeneous groups of machines and equipment; an efficient approach to mass production;
- object-based organisational structure - product-based organisation; a flexible design for diversified production;
- mixed organisational structure - integrating the two concepts; optimising production flows by combiningapproaches.

For the *object-based production type*, the may mention the following characteristics (see Fig.1.6) :

- the organisation of the departments is identical to the technological production type;
- each department produces only one type of product;

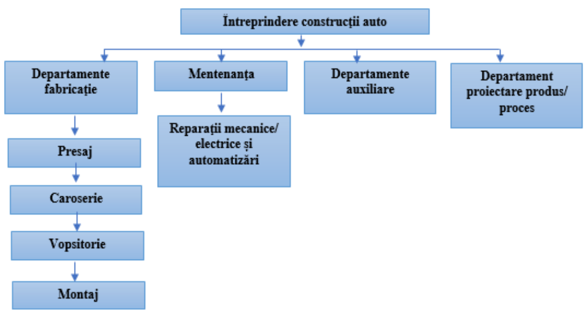


Fig.1.6 - Representation of Object Production Type

For the ***mixed production type***, the following characteristics can be mentioned (see Fig.1.7):

- organisation of mixed departments (part of the activities are organised according to the type of technological production; another part are organised according to production by object);

- is specific to small and medium seriesproduction.

The industrial production system is acomplex combination of resources, stages and flows that interact to produce the products and services needed by the market.

1.2.3.1. Elements of the production process

Within the production process, there are three elements that contribute to achieving the organisation's objectives:

- technological operations;
- control operations;
- transport and storage operations.

Procedural approach

In an organisation based on the process approach, several principles and requirements areapplied to ensure effective functioning and achievement of objectives.

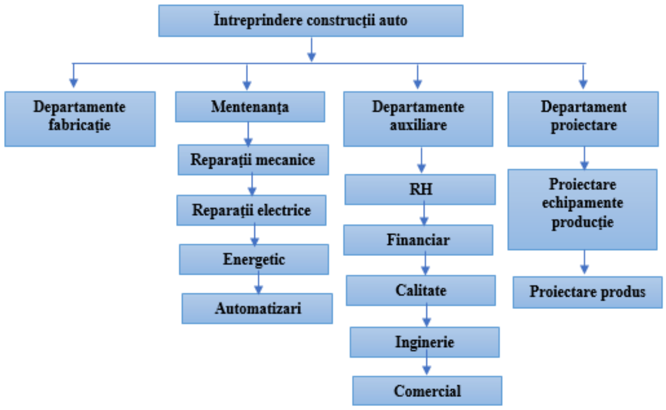


Fig.1.7 - Representation of Mixed Production Type

These include:

1. *__Principles for integrating the process approach into the organisation:__*

- hierarchical organisation - in addition to the traditional hierarchical structure, a horizontal organisation is added that focuses on processes that bring value to customers;

2. *__Requirements for applying the procedural approach:__*

- Process identification - all processes in the organisation, including outsourced ones, need to be identified to understand how they add value and to manage them effectively;

3. *__Key roles in the process-based organisation:__*

- Process owners - are responsible for process performance and improvement, ensuring thatprocesses deliver the desired results and align with the organisation's objectives.

1.2.4. Categories of processes

To describe any organisation, three types of processes can be classified:

- the processes of implementation;
- management processes;
- supporting processes.

1.2.5. Types of Production - definition, classification, importance

Categories of organisational processes

To describe any organisation, it can beanalysed in terms of three categories of processes (see Fig. 1.8):

- Processes of realisation
- Management processes
- Support processes

Fig. 1.8 - Production Line (Activity Chain)

1.2.5.1. Presentation of Types of Production

Practice has shown that, from an organisational point of view, there is no enterprise in which one of the three types of production - mass, serial or individual - is found in its pure form.

1.2.5.2. Production in series

The main feature of mass production is the repetition of the same production. Thus, seriesproduction involves regular production in medium or small batches or series with less stabilityover time.

1.2.5.2.1. Individual production

The main characteristic of individual production is that most of the work and products that are manufactured are orders with a very low and irregular degree of repeatability, or which are not repeated in manufacturing.

1.2.5.2.2. Production organisation in flow

Flow production organisation is a superior form of organisation of the productionprocess in industrial enterprises and is effectively applied in all cases where it is possible to permanently execute an operation or a group of products on certain workplaces, ensuring, as anecessary condition, a complete load.

Full job loading can be ensured if the relationship is respected:

$$Q - n * t > F * t \quad (2)$$

where:

Q = the volume of production to be made of the product under consideration;
*N * t* = time norm per product for the given operation;
*F * t* = available time pool of the machine on which the operation is performed.

The production process is an ordered set of technical activities and operations, organised in alogical and coherent sequence, which transforms raw materials and materials into finished or semi-finished products.

Organising production in flow involves a number of basic features that contribute to the efficiency and performance of the production process by:

- Dividing the technological process into equal or multiple operations;
- Distribution of the execution of operations by job ;
- Placement of jobs in order of execution of operations;
- The passage of work objects at a regulated pace;
- Use of appropriate means of transport:
- Concurrent execution of operations on all jobs.

Fig.1.10. Robotic Flow Line

By organising production in flow,companies can gain significant advantages, such as reducing production time, optimising the use of resources, increasing efficiency and product quality andthus gaining a competitive advantage in the market.

1.3. Synthesis of methods to improve the performance of manufacturing processes

One of the methods used by most companies in project management to increase the performance of manufacturing processes is Agile. It promotes rigorously tracked, managed project managementand encourages self-organisation, teamwork, accountability, promotes a set of best practicesthat enable fast and qualitative deliverables and an environment that aligns customer needs with company growth.

The composition of a Scrum team is small and has the following roles:

- the project manager;
- scrum Master (project manager;
- team.

Agile Scrum methodology is fast and simple, but it's not for everyone or every project.

- ***Prosos for Agile Scrum;***
- ***Cons for Agile Scrum.***

1.3.1. Principles Agile

The methodology is based on 12 principles [89]:

- customer satisfaction through fast project delivery;

- focus on change requirements, even at a late stage of development/implementation;
- Functional design on modules is delivered frequently;
- Close, day-to-day cooperation between the end client and the project team;
- Projects are built around motivated people who should be trusted;
- Face-to-face conversation is the best form of communication;
- Functional design is the main measure of progress;
- sustainable development capable of maintaining a steady pace;
- a continued focus on technical excellence and efficient implementation;
- simplicity is essential (the art of maximising the workload);
- self-organised teams;
- regular adaptation to changing circumstances.

Agile core values:

- individuals and interaction are more important than processes and tools;
- The completed project is more important than comprehensive documentation;
- working with customers is more important than negotiating contracts;
- Reacting to change is more than following a fixed plan.

The tools used by this SCRUM method:

- Product Backlog;
- Sprint Backlog;
- Increment (sprint goal).

Scrum steps:

- backlog organisation;
- Sprint planning;
- the sprint;
- stand up daily;
- Sprint review;
- Sprint retrospective.

The seven principles of TPS (Toyota Production System):

1. eliminates waste: - any activity that does not produce value is considered waste;
2. builds quality - achieving smaller, validated cycles of work;
3. knowledge assimilation - the team must always be open and receptive to new things andalways available for learning;
4. Deferral of commitment - involves a flexible approach to the process, leaving room for modification or improvement;
5. fast delivery - the work should be commensurate with the capacity of the project team, with shorter work cycles;
6. Respect for people - the project team must be engaged and focused on what they are doing;
7. optimising the whole process - the implementation of a project must be looked at as a whole bythe project team.

Relationship between AGILE and LEAN methodologies

- The iterative development that underpins Lean methodology is the equivalent of Agile principles of rapid delivery and delayed accountability;
- is based on short production cycles,;
- The Agile method is used to "discipline" the project management process.

1.3.2. Design Thinking, along with Lean and Agile - ***emphasizing***, ***ideating***, ***testing***.

- ***Design Thinking*** - the artist, the creative side;
- ***Lean*** - the scientist, the experimentation part;
- ***Agile*** - the builder, the production side itself.

or,

- ***Design Thinking*** - soul, vision and empathy;
- ***Lean*** - brains, decision making and risk management;
- ***Agile*** - the engine, quality, efficiency and optimization.

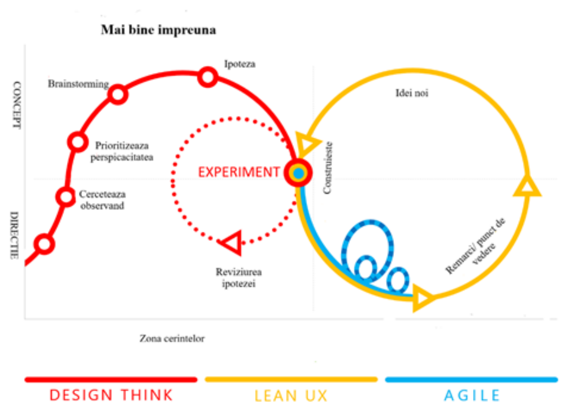


Fig. 1.4 – The Relationship Between Agile, Lean, Design Thinking

Design Thinking is a set of principlesthat has been regarded as the secret craft of design agencies, but in reality it is a little different; it is important because of new technologies and modern businesses that have evolved and become more complex.

It has its roots in a multitude of areas, such as:

- psychology;
- anthropology;
- cognitive psychology;
- philosophy;
- urban architecture;
- engineering;
- industrial design;
- materials science;
- chemistry;
- human-computer interaction;

The three pillars of Design Thinking:

- business;
- economy

- **Empathy** - Deep understanding of the needs of those you are creating for;
- **Idea** - Generating a multitude of ideas through different methods;
- **Experimentation** - Testing ideas through prototyping.

Advantages of using Design Thinking:

- helps uncover people's previously unmet needs on which to build innovation;
- reduces the risk associated with new product launches;
- generates potentially disruptive solutions, not just incremental ones;
- helps organisations learn faster.

1.4. Improving the performance of production processes through digitisation projects

Manufacturing line digitization projects involve reducing paper consumption by introducing digital information and digitizing the workstation through a smartphone and tablet compatible web app that provides a function for each initiative related to a digital workstation.

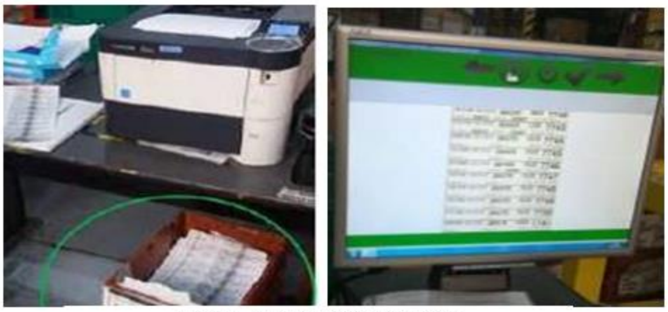


Fig.1.11 – Project "0Paper": Before/After

0Paper

Instant benefits - promoting an ***e-paper*** solution in manufacturing lines became achallengethat had to be triggered because, in many automotive manufacturing plants, the digitisation of production systems was the key point in their development, quality assurance and end customer satisfaction (see Fig.1.11).

Project objectives (see Fig.1.12):

- reducing the number of papers printed in the manufacturing process and replacing them withscreens;
- identifying sources of non-value in jobs;
- improving job performance.

Estimated earnings - approx. 70 k€ resulting from:

- Recovering printers from the production line and reducing related consumables;
- reducing the number of alerts for printing equipment;
- other associated costs (renewal of the printer fleet, rebuilding of computer networks, replacement of informationtransfer ports, etc.).

The analysis of the consumables used in the manufacturing process for 1 year resulted in the following data in Fig.1.13.

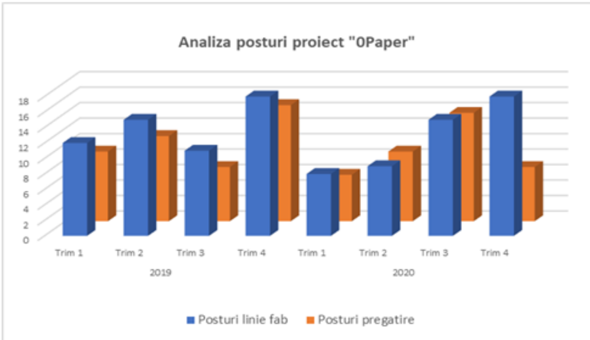


Fig. 1.12 – Project "0Paper" Position Analysis

Digitisation of the workstation (DWS)

Deployment of tablets in each workstation, allowing operators to know and respond to the activities carried out in the manufacturing line.

The gains of digitisation :

For the operator:

Advantages of implementing the project digitization workstation:

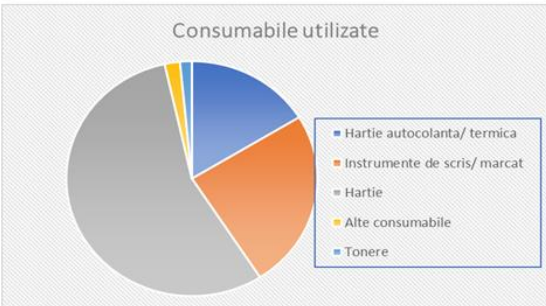


Fig. 1.13 – Analysis of Consumables

- remove non-value added for operators by manually validating the switch to the next car;
- Manual validation removal for all screens in the production line;
- remove labels accompanying the kit with references;
- decrease preventive maintenance time and alerts (missing parts from the kit; vehicle degradation in the work process; maintenance problems; parts out of specification, etc.).
- miscellaneous information - about the vehicle; exotic variants warning (rare); non-compliant fitting alerts ;
- trouble-free activity start - secure connection to digital station; digital station start validation; non-functional tools warning; vehicle completion signal (first).

For the supervisor:

- operator call resolution: quick call view; alert classification (manufacturing; logistics; physiological, etc.);
- re-call alert; call waiting type view; call hang-up.

Digitising these compliance verification operations can only bring quality, high responsiveness and ultimately customer satisfaction (see Fig.1.14).

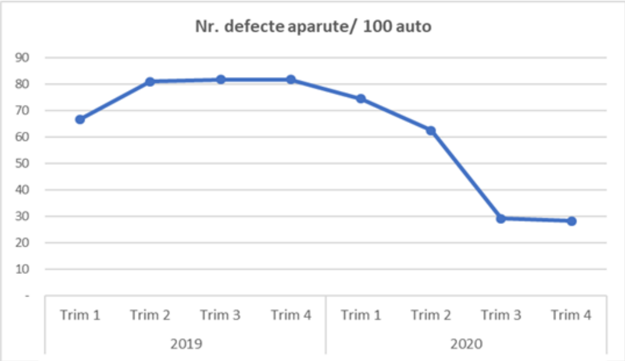


Fig. 1.14 – Evolution of Quality Indicator

The digitisation project involves a computer programme to manage the resulting values in all workstations that are subject to regulatory requirements. As a tool for the operators performing the verification operations, measuring equipment (with embedded memory) will be available which stores the measured values, correlated with the identification code of each vehicle and which can be downloaded at the end of the verificationcycle in a computer or can communicate wifi and transmit recorded data in real time.

1.5. Formulation of the objectives of the thesis

The objectives are the paths the researcher will follow in the work to achieve the desired results. In the case of this work, the objectives were set in accordance with the need to address and solve problems in the sphere of production process optimization.

Subject of the research

The main objective of the scientific research is to formulate a generalised model for the analysis of production flows as a basis for decisions to apply methods to improve their performance.

Specific objectives

The main objective will be achieved through the following specific objectives:

- identify current issues in the field of production process optimisation;
- analysing methods to increase the performance of production processes;
- mathematical formulation in the form of a multi-criteria equation of the generalised model for the analysis of production flows;
- Experimental investigation of the impact of the automation decision through robotisation and validation of hypotheses on increasing the performance of production processes.

CHAPTER 2 - THEORETICAL DEVELOPMENT OF THE PROBLEMS OF IMPROVING PRODUCTION PROCESSES

2.1. Elements of production processes - types, classification, definition, importance

The elements of production flows are the fundamental components of production activities that contribute to the realisation of products or services within an enterprise, are essential in the management and optimisation of production processes and are specific to each type ofactivity, end product and manufacturing methods used.

Types of production flows :

1. Materials
2. Tools
3. Workers
4. Production methods and technologies
5. Information flow
6. Quality control
7. Production planning and scheduling
8. Logistics and management chain supply chain
9. Flow of financial information
10. Environment and sustainability.

2.2. Methods to improve production processes

A direct observation is valuable because it can identify:

- the level of correlation of one or more activities;
- Recurring problems that have not been dealt with responsibly or at all;
- the employment rate of operators;
- failure to follow clearly defined milestones;
- solving problems in all sectors;
- understanding of the process and chaining of activities in a small percentage, with no possibility of evolution;
- imbalances in resource allocation;
- lack of evaluation criteria for the work process.

Based on the studies, the idea is promoted that the productivity of an industry is influenced byits productivity growth and is also influenced by the organisation that is positioned at the centre of the network.

An industry is in a central position if it has a large number of trading links between industries.

2.3. Improving production efficiency by simulating the cellular manufacturing model

The flexible cellular manufacturing model has been developed, tested and implemented to improve the efficiency of manufacturing processes within an organisation, and is a tool that allows experimentation with different manufacturing techniques to identify the best solution without actualimplementation.

The advantages are:

- creating the mass production effect, setting up workshops specific to a particular type of production;
- reduced installation/modification time;
- cost reduction due to simplified material flow;
- ease in redesigning a new manufacturing layout;
- the process of checking the accuracy of the simulation is high, using statistical techniques.

2.4. Methods to improve process management production

For most of those analysing the performance of industrial enterprises, process management is an important area of a production department's activities that presents systems, procedures, methodsand tools for achieving high and sustainable performance, improving processes and meeting commitments to employers (see Fig. 1.13).

Process evaluation and measurement is based on the identification of internal performance indicators, specific to each activity/process and related to common attributes - end customer,inputs/outputs and boundaries of the process under analysis.

Internal process performance indicators must be determined in a way that allows the achievement of key indicators that track the implementation of the performance strategy to be monitored.

Actions to increase and streamline performance can be grouped into six categories:

- ***efficiency*** and ***effectiveness of*** the process;
- ***quality*** - the level of satisfaction of customer requirements and expectations;
- ***punctuality*** - based on customer requirements;
- ***productivity*** - as the value added of the process composed of the value of labour and capital consumption;
- ***safety*** - measures the overall health of the employees' working environment.

There are three types of performance measurement indicators:

- outcome indicators (KRIs), which measure the results of several actions and focus on a long period of time;
- performance indicators (KPIs), require corrective actions, having a positive impact on all indicators;
- Process Performance Indicators (PPIs), are found between outcome indicators and performance indicators.

2.4.1. Measuring the performance of the holistic process

This system requires relevant data on the performance of different systems using operational information and is designed based on the process of activities at the organisation level.

Theoretical studies on process performance analysis have led to the development of thefollowing typologies of process indicators:

- universal process indicators that are used for various performance measurements;
- indicators for measuring production processes, are necessary for operational production management;
- indicators for measuring indirect productive processes - those processes that are carried outbefore the production process, during production and after the production stage.

2.4.2. Lean manufacturing principles in increasing managerial performance

According to the studies, five main areas for management improvement have been identifiedin low-performing organisations:

- Managers need to be highly technically competent;
- Managers need to have a clear picture of their customers;
- managers must have performance indicators displayed and updated,
- managers need to be involved in process improvement;
- Managers should do their best to recognise employees' achievements.

2.5. Other ways to increase performance

The application and performance management of manufacturing processes worldwide has become anindispensable activity of all organisations focused on productivity, turnover growth and product quality, with a focus on internal factors imperative for success.

The internal factors analysed are: structural analysis, management, technological processes, organisational culture and employee engagement.

The main tool used in the analysis of information and material flows is VSM (Value Stream Mapping), which is a classic tool for the analysis of low performance manufacturing processes, an economical method for the presentation and improvement of material flows in manufacturingprocesses.

After several years of study, Toyota has shown that implementing Lean manufacturing can have many barriers and obstacles, but the benefits outweigh all the difficulties and efforts.

2.5.1. Risks encountered in the implementation phase of methods to increase performance

Like any change from the daily "routine", the implementation of new methods is viewed with suspicion/restraint by many employees; if the organisation does not have a developed organisational culture,it is difficult to achieve a "breakthrough" to improve performance.

The most important point in organisations with a weak organisational culture is the creation ofan organisational learning project, a process of training and implementing new visions so thatclassic tools can be gradually and easily replaced by modern ones to streamline manufacturing processes.

Any performance improvement project muststart by comparing the current situation with the target set, to identify the gap to be closed andanalyse the causes; once the gap has been identified, a detailed action plan must be drawnup.

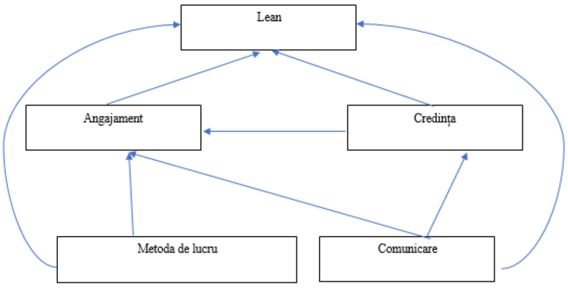


Fig. 2.2 - Predictive Factors Influencing the Implementation of a Modern Method

2.6. Monitoring production flows

Monitoring elements of a flow production line

This involves inspections, internal audits, regula r reviews and customer assessments.

Via monitoring constant monitoring a data by production and comparing them with established performance indicators, shortcomings can b e identifiedand corrective action taken to optimise processes.

2.6.1. Monitoring and adjusting production processes

Issues related to monitoring and adjusting production processes [73]:

1. Process performance monitoring;
2. Monitoring and control systems;
3. Performance indicators (KPIs);
4. Process adjustment;
5. Use of advanced technologies.

2.6.2. Modern methods of monitoring production

Monitoring systems are integrated production organisation systems and are known under thefollowing names [124]:

- Linear programming method;
- Production organisation methods using critical path analysis (CPM and PERT;
- Just in Time" method (JIT;
- Tree method;
- Production functions method.

<u>Critical Path Method (CPM) critical path analysis,</u>

is a time-focused critical path analysis procedure for a project. This critical path represents a sequence of critical activities and events that form a continuous path between the beginning and the end of the project.

CPM is used to map the elements of a project (activities, events) to the elements of a graph (arcs and nodes), highlighting temporal sequence features.

Critical path analysis using the CPM method:

To calculate the critical path using the CPM method, we need to follow the following steps:

- Construct the CPM network diagram, which contains the activities as nodes and thedependencies between them as arcs;
- calculating the duration of each activity (D);
- calculating this start (ES) and finish (EF) for each activity;
- calculating this late start (LS) and late finish (LF) for each activity;
- calculation of the activity float (F) for each activity;
- identifying activities with zero float - this forms the critical path.

This MATLAB code (see Fig.2.3) calculates the Start Time (ES) and End Time (EF),the Late Start Time (LS) and Late End Time (LF), the Float (F) and identifies critical activities(with Float zero). Thus, one can analyze and identify the critical path of a project using the CPM method.

PERT method (Repeated Programme Evaluation Technique),

provides valuable information in theprocess of managing complex projects,taking into account possible variationsin the execution times of activities. It isused in the production of complex units, where operations must be carried out ina certain order and within set deadlines. The PERT method allows the calculation of the average time tocomplete the project, the identification of activities and estimates the likelihood of achieving planned deadlines. In the PERT network, the projectis modelled graphically, illustrating the logical and chronological relationships between component activities andevents.

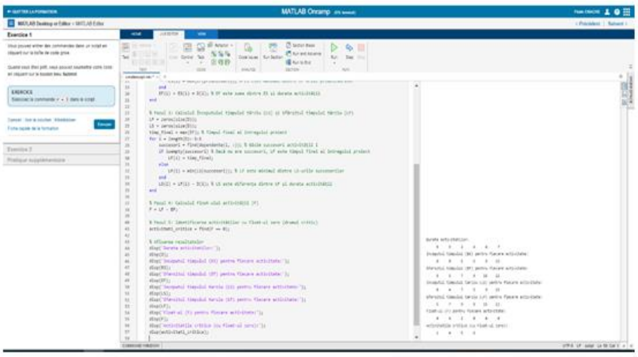


Fig. 2.3 – Critical Path Analysis Representation Using the CPM Method in MatLab

Just in time" is a strategic and operational approach used in production management. The aimof this method is to organise production in a continuous flow, ensuring proper coordination of lead times, product quality and costs. This system aims at reducing stocks of raw materials, materials, parts, sub-assemblies and production [65].

Some key details about the "Just in time" method:

- Reducing costs;
- Continuous production flow:;
- Quality as a priority:;
- Cooperation with suppliers:;

Flexible production;

- Reduced changeover times:;
- Risk management:.

Decision tree method

It is a method of analytical approach used to determine and analyze risks, uncertainties and probabilities in the manufacturing process; it involves the use of a decision tree, which contains elements such as decision points, alternatives, opportunity points, natural states and gains.

Production functions method

It represents a correlation between the output of a production activity, such as gross domestic product or value added, and the factors that determine it, such as the structure and productivity of the enterprise, the use of capital or the degree of re-engineering.

CHAPTER 3. CONTRIBUTIONS ON MODELLING MATHEMATICS OF PRODUCTION PROCESS OPTIMISATION

3.1. Mathematical modelling used in production flow analysis

Mathematical modelling of production process optimisation involves optimising costs, cycle times, technology levels, energy consumption through mathematical models used in the analysis of production flows.

Process performance determination

Process performance is assessed against two criteria, effectiveness and efficiency:

- Effectiveness - the degree to which the outputs of a process meet the needs and expectations of their customers.
- Efficiency - the degree to which resources are minimised and losses eliminated.

Efficiency is critical to the organisation as it allows the cost of operating key processes tobeassessed. The cost of the core business is the best tool to use. The principle underlying the cost of the basic activity is as follows: products and services are produced through production activities, these activities consume resources and the consumption of resources involves costs.

3.2. Multi-criteria optimisation of production flows,

(optimisation of costs, cycle time, level of technology, energy consumption)

Multicriteria equation for verification of AGILE methodologies (Kanban and Scrum)

This multi-criteria equation can be constructed to take into account several important factorssuch as delivery time, quality of delivered products, customer satisfaction, team efficiency, etc.

Defining the relevant variables for constructing the equation:

- TDL (Delivery Time) - represents the average time required to complete a project from initiation to delivery of the finished product;
- Product quality - can be measured, for example, in terms of defects or errors reported in the finished product;
- Customer satisfaction - can either be assessed through surveys or direct feedback received from customers on the product delivered;
- Team efficiency - can be calculated by the number of completed tasks in relation to the total number of planned tasks;
- Project costs - includes the total costs of the project, including human and material resources allocated.

The multi-criteria equation might look like this:

$$\text{Project\_performance} = w1 * (1/\ TDL) + w2 * \text{Product\_quality} - w3 * \text{Customer\_satisfaction} + w4 * \text{Team\_efficiency} - w5 * \text{Project\_costs} \quad (3)$$

where:

w1,w2, w3, w4 and w5 are the weights for each criterion in the assessment.

These weights can be defined according to the importance of each criterion for the specific organisation or project.

The result of the "Project_performance" equation will be a score reflecting the overall assessment of the project performance according to the specification criteria and assigned weights. The higher the score, the better the project performance is considered to be in terms of the criteria assessed.

The purpose of this equation is to provide a measure of the overall performance of the project implemented using Agile methodologies. Using the weights, the organisation can adjust the importance of each criterion according to its specific needs and priorities (see Fig.3.1).

In this way, the multi-criteria equation becomes a valuable tool for project managers and the project team to successfully achieve projectobjectives and ensure agile and efficient development of products and services.

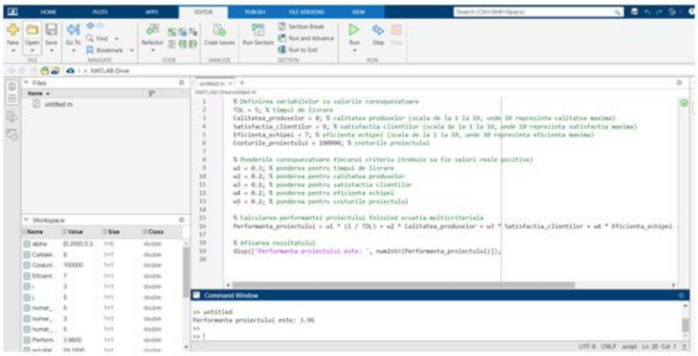


Fig. 3.1 – Production Flow Optimization – Multicriteria Equation Represented in MatLab

General multi-criteria equation for implementing new projects:

Multicriteria equations are used to evaluate and select the best solutions in a multi-criteria decision-making process. To create a general multi-criteria equation for implementing new projects using AGILE, LEAN and DESIGN THINKING, we first define the relevant criteria and their weights. Then, we will assign each method a value for each criterion. To do this, we will use importance coefficients (weights) for each method, so that we can adjust the influence of each method on the final result.

We assume that we have the following criteria relevant to the evaluation of theimplementation of a new project:

- efficiency (weighting: α1);
- the quality of the resulting product (weighting: α2);
- project flexibility (weighting: α3);
- costs (weighting: α4);
- time required for completion (weighting: α5).

The multi-criteria equation has the following form:

$$\text{Result\_method\_i} = \sqrt{\sum j = 1 n \alpha j \cdot (\text{Valoare\_metoda}(i, j))2} \quad (4)$$

where:

- Result_method_i - represents the result obtained for method "i" (in this case, Agile, Lean or Design Thinking);
- Method_value (i, j) - represents the value assigned to method "i" for criterion "j";
- N - is the total number of criteria (in our case, n = 5);
- αj - are the weights assigned to each criterion (in this case, the values in the vector "alpha".

Explanation:

The multi-criteria equation is used to evaluate different methods or solutions based on important criteria (in the example shown, we have three methods: Agile, Lean and Design Thinking and all methods will be evaluated based on five criteria).

For each method, a set of values for the five criteria is assigned; each value is multiplied bythe corresponding weights (the elements of the "alpha" vector), and the results are summed and finally, the summation is applied to a radical to obtain the final result for each method.

The multi-criteria equation allows us to evaluate and compare the performance of different methods (Agile, Lean and Design Thinking, in this case) based on important criteria; the results obtained for each method allow us to indicates how well the methods perform against the given criteria and helps us to make informed decisions in implementing new projects (see Fig.3.2).

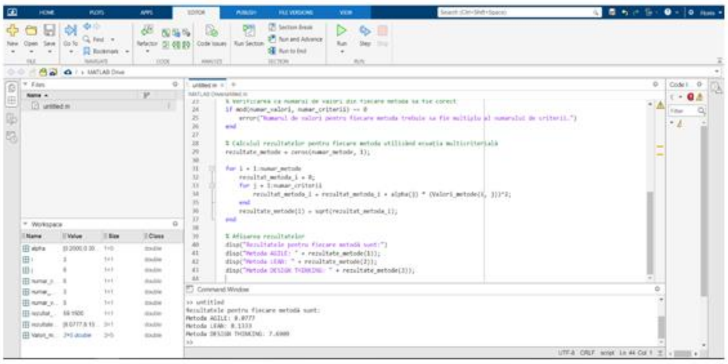


Fig. 3.2 – Production Flow Optimization – Multicriteria Equation Represented in MatLab

It is important to adjust the weights (values in the vector ("alpha") according to the importance of each criterion for our project, as these weights may influence the results and reflect ourpriorities; also,
The equation can be customized with several criteria or methods, depending on the specifics of the project and our needs.

Multicriteria equation for critical path analysis by CPM method:
Suppose we have a project consisting of a set of activities, represented by nodes in anacyclic oriented graph (CPM network diagram).
To calculate the critical path using the CPM method, we need to follow the following steps:

- Construct the CPM network diagram, which contains the activities as nodes and thedependencies between them as arcs;
- calculating the duration of each activity (D);
- calculating the start (ES) and finish (EF) for each activity;
- calculating the late start (LS) and latefinish (LF) for each activity;
- calculation of the activity float (F) foreach activity;
- identifying activities with zero float - this forms the critical path.

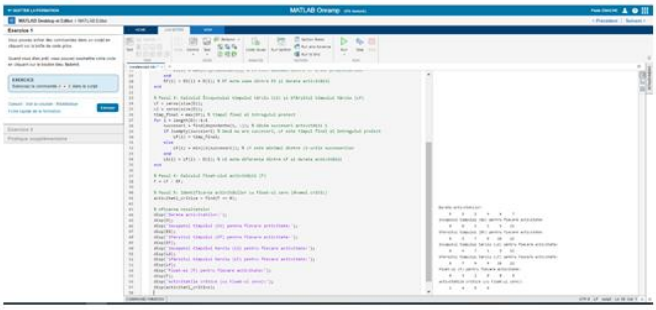


Fig. 3.3 – Critical Path Analysis by PERT Method Represented in MatLab

This MATLAB code (see Fig.3.3) calculates the Start Time (ES) and End Time (EF), the LateStart Time (LS) and Late End Time (LF), the Float (F) and identifies critical activities (with Float zero). Thus, one can analyze and identify the critical path of a project using the CPM method.

Multicriteria equation for critical path analysis by PERT method:
Suppose we have a project consistingof a set of activities, represented by nodes in an acyclic oriented graph (PERT network diagram). For each activity, wecan have the following criteria:

- Estimation time (TE): the time allocatedto complete the activity, expressed as a single number;
- optimal time (TO): shortest time

in which the work can be completed, based on the best working conditions;
- pessimistic time (PT): the longest time in which the work can be completed, taking intoaccount possible delays or obstacles;
- most probable time (TM): the most probable time when the work can be completed, given normal working conditions.

The formula for calculating the time estimate (TE) for each activity using the PERT method is:

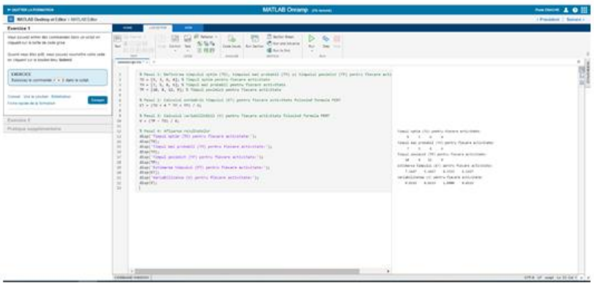


Fig. 3.4 – Critical Path Analysis by JIT Method Represented in MatLab

$$ET = (TO + 4 * TM + TP) / 6 \quad (5)$$

This formula takes into account that the optimal time (TO) contributes a weight of 1 to the time estimate, and the more likely time (TM) and the pessimistic time (TP) contribute a weight of 4 each. A weighted average is taken to obtain the final time estimate (TE).

This MATLAB code (see Fig.3.4) calculates the time estimate (ET) and variability (V) for each activity using the PERT formula. These estimates and variabilities can then be used to analyze and plan the project using the PERT method.

Equation for critical path analysis using the JIT method:

The Just-in-Time (JIT) method is a production management approach that aims to reduce inventory and lead time to minimise costs and ensure efficient and flexible production. In a JIT system, materials are brought to the production line exactly when they are needed, thus eliminating excess inventory and waste.

To evaluate the performance of the JIT method, we can use a multi-criteria equation that combines several key factors of the production system. This equation has the general form:

JIT-Score = α * costs + β * delivery_time + γ * stocks + δ * scrap_rate + ε * flexibility where:

- α, β, γ, δ and ε are weights (coefficients) indicating the relative importance of each criterion inthe evaluation of the system. These weights should satisfy the condition $\alpha + \beta + \gamma + \delta + \varepsilon = 1$;
- costs, represents the total production costs in the JIT system;
- delivery_time, represents the average delivery time of finished products to customers;
- Stocks, represents the average level of stocks of materials or products in the production process;
- Defect_rate, represents the percentage of defective or non-conforming products in production;
- flexibility, the extent to which the production system can respond quickly to changes or newrequirements.

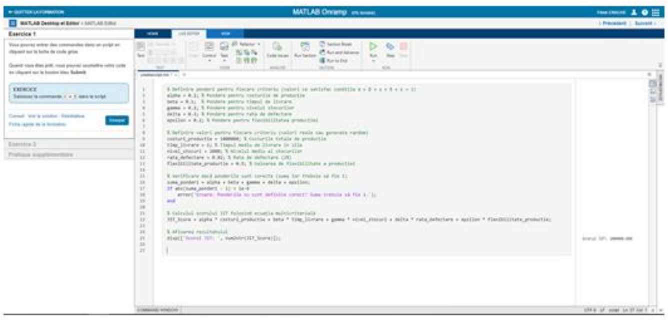


Fig. 3.5 – Critical Path Analysis by Decision Tree Method Represented in MatLab

The final JIT score, obtained by combining the weights and values of the criteria, provides a measure of the performance of the project or production system, allowing different options or alternatives to be compared and evaluated (see Fig.3.5).

Multicriteria equation for critical path analysis using Decision Tree method

Equations multicriteria equations generalize the decisionmaking process when we have morethan one criterion to consider and canbe defined as follows:

where: $F(X) = \alpha_1 * f_1(X) + \alpha_2 * f_2(X) + \alpha_3 * f_3(X) + ... + \alpha_n * f_n(X)$ (7)

- $F(X)$ is the global decision evaluation function, which must be maximized or minimized, depending on the nature of the problem;
- $X = (x_1, x_2, x_3, ..., x_m)$ is the vector of decision variables, i.e. the values we can choose for each criterion;
- $\alpha_1, \alpha_2, \alpha_3, ..., \alpha_n$ are the corresponding weights of each criterion, with $\alpha_i \in [0, 1]$ and $\sum\alpha_i = 1$,reflectingthe relative importance of each criterion in the decision-making process;
- $f_1(X), f_2(X), f_3(X), ..., f_n(X)$ represent the evaluation functions of each criterion, which may be defined differently depending on the nature of the criterion and the available data

For the "Decision Tree Method", $f_1(X)$, $f_2(X)$, $f_3(X)$, ..., $f_n(X)$ can be functions that evaluate performance, costs, quality, response times and any other relevant criteria in monitoring production. Suppose we have a choice between two cars (Car A and Car B) that we want to buy, and to make the right decision, we are interested in several aspects: price, fuel consumption and safety performance.

Each will be represented by a specific function that takes into account the values of each criterion for each machine. For example, suppose we have the following functions:

- $f_1(X)$ = the price of the car (with lower values being preferred, because we wantto spend less money);
- $f_2(X)$ = fuel consumption of the car;
- $f_3(X)$ = score obtained in safetytests.

1. Each function will be multiplied by a certain weight (α_1, α_2, α_3) that reflects the relative importance of each criterion for us. For example, suppose that for us the cost of the car (price) is more important than fuel consumption, and safety is even more important. We can have:

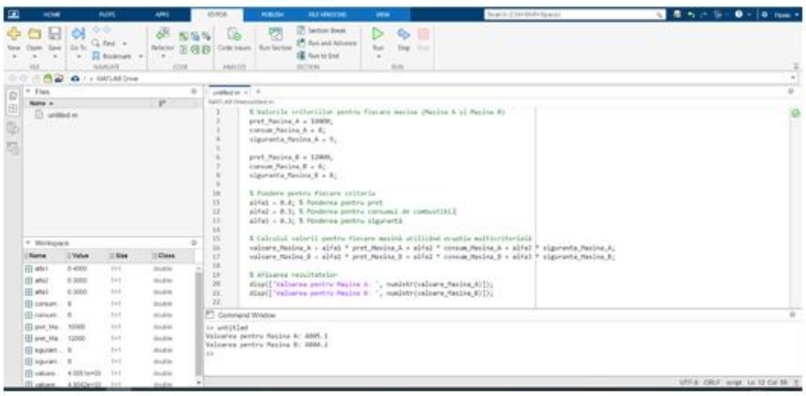


Fig. 3.6 – Critical Path Analysis by Production Function Method Represented in MatLab

- $\alpha_1 = 0.4$ (40% price significance);
- $\alpha_2 = 0.3$ (30% importance for fuel consumption);
- $\alpha_3 = 0.3$ (30% safety significance).

2. The final equation is constructed by summing all these components:

$$F(X) = \alpha_1 * f_1(X) + \alpha_2 * f_2(X) + \alpha_3 * f_3(X) \quad (8)$$

.The machine that gets the highest result in the equation will be the best choice for us, taking into account our priorities and the importance of each criterion (see Fig.3.6).

Multicriteria equation for critical path analysis by production function method

The production function method is used in economics and cost analysis toquantify the relationship between inputs and outputs in a firm or industry. This can help to determine the efficiency and yield of production.

1. Function with technical progress (Cobb-Douglas):

The Cobb-Douglas function is a simple and widely used production function that expresses the relationship between output and inputs in an elastic way. The general formula for the Cobb-Douglas function is:

$$Y = A * (L^{alpha}) * (K^{beta}) \quad (9)$$

where:

Y is the output;

L is the size of the labour force; K is the capital (input);

A, alpha and beta are constant parameters, with A being a measure of technology or technical progress;

2. Constant Elasticity of Substitution(CES) production function:

The CES function is a production function that takes into account substitution between factors of production. The general formula for the CES function is:

$$Y= A * [(a * (L^{rho}) + (1-a) *(K^{rho}))^{(1/rho)}] \qquad (10)$$

where:

Y is the output;
L is the size of the workforce;
K is the capital (input);
A and **rho** are constant parameters, with rho representing the elasticity of substitution and "a"being ameasure of the weight of each factor of production.

Irma Adelman production function: is another production function used to analyse therelationship between output and inputs.

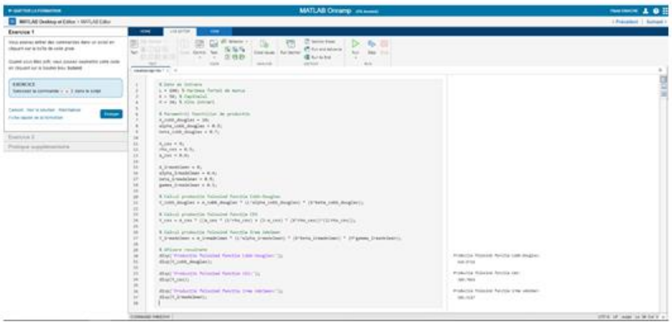


Fig. 3.7 – Analysis of the critical path by the method of production functions, represented in MatLab

The general formula for Irma Adelman's position is:

$$Y = A * (L^{alpha}) * (K^{beta}) * (M^{gamma}) \qquad (11)$$

where:

Y is the output;
L is the size of the workforce;
K is the capital (input);
M stands for other inputs such as raw materials or technology (input);
A, alpha, beta and gamma are constant parameters, with A being a measure of technology or technical progress, and alpha, beta and gamma representing the elasticity of output at each input factor.

Multicriteria equation on cost-quality optimization (manufacturing flow optimization)

I propose a simplified multi-criteria equation with 3 criteria: cost (C), cycle time (T) and technology level (N). I will assign weighting coefficients w1, w2, w3 to each criterion, representing their relative importance. For the choice of the weighting coefficients w1, w2, w3 I evaluated the relative importance of each criterion in the specific context of productivity growth.

Cost (C) - is an important criterion in increasing productivity and can be expressed infinancial terms including material costs, labour costs, equipment costs, plus other expenses associated with production (the lower the cost, the more favourable the variable is for increasing productivity).

Cycle time (T) - is the time required to complete a production cycle; may include processing time, waiting time and other necessary activities. The shorter the cycle time, the more favourable the variable is for increasing productivity.

Level of Technologisation (N) - represents the degree of use of modern technology and automation in the production process. This criterion may include the use of robots, numerically controlled machines, computer systems, etc. The higher the level of technology, the more favourable the option is for increasing productivity.

$$F= w1*C+w2*T+w3*N$$

The equation follows: where:

W1=0.5; w2=03; w3=0.2F = 0.5*C+0.3*T+0.2*N

(12)

F - is the value obtained from the evaluation of the productivity increase option;

C - represents the score assigned to the cost criterion;T - is the score assigned to the cycle time criterion;

N - represents the score assigned to the criterion level of technologisation.

Applying the above equation, we obtain a result F which will indicate how favourable the option is in terms of productivity growth. The higher the value, the more suitable the variant is considered to be for the intended purpose.

Implementing a robot cell can help optimise manufacturing flows by reducing human error, increasing efficiency and productivity and thereby improving product quality and reducing production costs.
By simulating and analysing manufacturing flows, potential inefficiencies or bottlenecks can be identified and eliminated, thus optimising the performance and effectiveness of the entire production system.

C1 = 0.85
C2 = 0.76
C3 = 0.92
w1 = 0.5
w2 = 0.3
w3 = 0.3

Thus the equation becomes:

$$Z = 0.5 * 0.85 + 0.3 * 0.76 + 0.3 * 0.92 = 0.425 + 0.228 + 0.276 = 0.929 \quad (14)$$

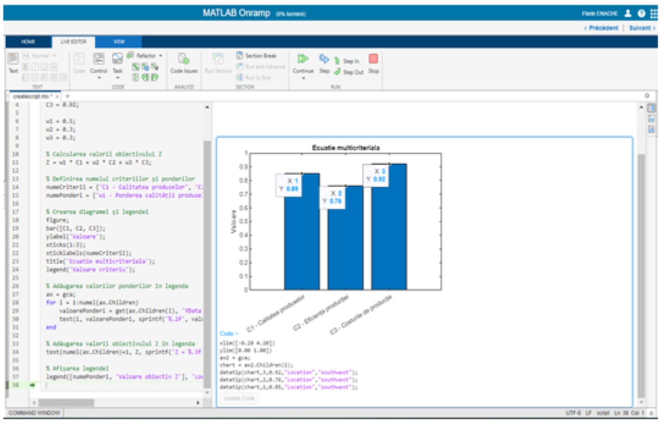


Fig. 3.9 – Graphical Representation of Multicriteria Equation for Theoretical Analysis and Optimization of Manufacturing Flows

In this case, the value of the Z target is a measure of the overall optimisation of manufacturing flows, taking into account the quality of the products, production efficiency and production costs.
The final objective is to maximize the value of the Z objective, which indicates an efficient and balanced optimization of manufacturing flows (the higher the value of the Z objective, thebetter the optimization of manufacturing flows is considered).

Multi-criteria equation for discrete, continuous and combined models for simulation optimization of manufacturing flows

The multi-criteria equation can take a general form, with weights associated with each criterion. The weights reflect the relative importance of each criterion in the decision process. Depending on the specifics of each project or application, these weights can be adjusted to achieve results relevant to the proposed objectives.

After filling in the weights in the multi-criteria equation, we can obtain a numerical result that represents the score or performance of each scenario or model evaluated in the manufacturing flow simulation optimization.

The result will be a value that reflects the quality of each scenario in relation to the criteria considered.
Example: for each scenario evaluated, we will have a set of values for each criterion (production time, costs, resource efficiency, product quality, etc.) and the weights associated with each criterion.

The multi-criteria equation for discrete, continuous and combined models is defined by weights assigned to each criterion; these weights indicate the relative importance of each criterionin the optimisation process (we have four criteria: production time - continuous model; costs - discrete model; resource efficiency - combined model; product quality - continuous model).

The weights for each criterion are defined as follows:

- alpha - for production time (discrete model);
- beta - for costs (discrete model);
- gamma - for resource efficiency (combined model);
- delta - for product quality (continuous model).These weights (see Fig.3.10) satisfy the condition that their sum is equal to 1, to reflect the total importance of all criteria (in MATLAB thevalues for each criterion are defined as real values for the purpose of illustration).

Multicriteria equation performa**nce evaluation of therobot cell:**

In order to formulate the multi-criteria equation, relevant criteria for evaluating the performance of the robot cell must be identified. Depending on the available information and the specific objectives of the system, I will consider the following criteria:

- Efficiency;
- Reducing costs;
- Product quality.

Performance = w1 * Efficiency + w2 * Cost reduction + w3 * Product quality (15)where:

w1, w2, w3 represent the weighting coefficients for each criterion and reflect the relativeimportance given to each.

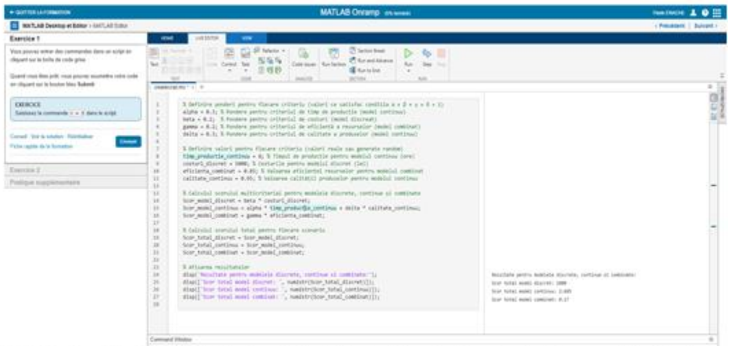


Fig. 3.10 – Simulation-Based Optimization of Manufacturing Flows for Discrete, Continuous, and Combined Models Represented in MatLab

Efficiency, Cost Reduction, Quality are the normalised scores for each criterion, which can beobtained by evaluating the performance of the robot cell in each area.

w1=0.5; w2=0.3; w3=0.3

This equation allows the calculation of the performance value for each variant evaluated,taking into account the relative importance of the three criteria: Ef=0.76; Rc=0.92; Cp=0.85.

Performance (Z) = 0.5 * Efficiency + 0.3 * Cost reduction + 0.3 * Product quality =0.5 * 0.85 + 0.3 * 0.92 + 0.3 * 0.92 = 0.425 + 0.228 + 0.276 = 0.929

After writing the Matlab code the following results:

- The diagram generated inMATLAB (see Fig.3.11) is a bar chart, which helps us visualize the performance of the robot cell according to criteria.
- On the horizontal axis of thediagram we have the names of the criteria considered: Efficiency, Cost reduction and Product quality.These are the aspects we want to evaluate in terms of the performance of the robot cell.
- On the vertical axis we have thescale of performance values, which varies according to the scores obtained for each criterion. The higher a bar is, the higher the scorefor that criterion, indicating better performance in that area.

Each bar represents a criterion, and its height is proportional to the score for the criterion (e.g. ifthe bar for the criterion "Efficiency" is taller than the other bars, it means that the cell scores higher interms of production efficiency). Above each bar the corresponding score value is displayed, rounded to two decimal places, allowing us to clearly see the values associated with each criterion and compare them with each other.

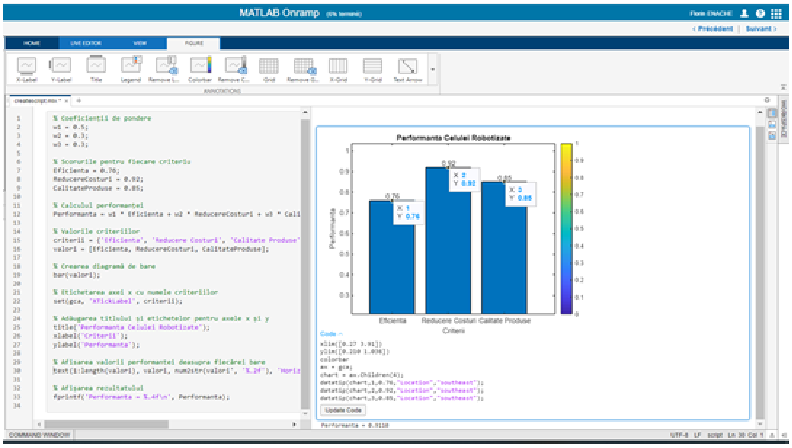


Fig. 3.11 – Multicriteria Equation Representation for Evaluating the Performance of the Robotic Cell

The implementation of the robot cell, in the machining process, brings significant benefits in terms of increased productivity, cost reduction, improved quality and optimized resource utilization, all of which contribute to increased competitiveness and overall business efficiency.

Multicriteria equation for assessing the level of performance growth:

$$\text{maximizes } f(x) = (w1 * f1(x)) + (w2 * f2(x)) + (w3 * f3(x)) + \ldots (wn * fn(x)) \tag{22}$$

where:

f(x) - is the vector of objectives or performance criteria;

x - represents the decision variables or parameters of the system or process;

fi(x) - represents each objective function corresponding to a performance criterion. For example, f1(x) may represent profit growth, f2(x) may represent productivity growth, f3(x) may represent cost reduction, etc.;

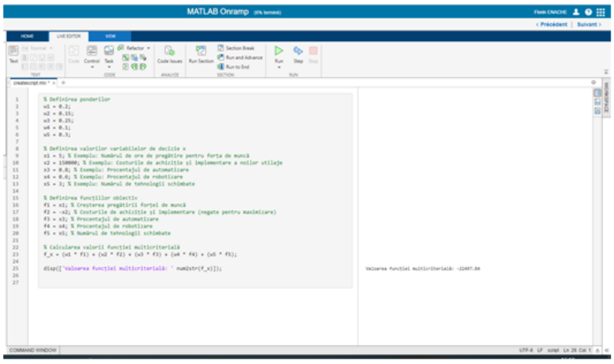


Fig.3.12 – Evaluation of the Growth Level of Performance Based on Multiple Criteria Represented in MatLab

wi - represents the corresponding weights for each performance criterion. These weightsreflect the relative importance of each criterion in assessing performance;

n - represents the total number ofperformance criteria

This multi-criteria equation allows us tomake an overall assessment of the level of performance growth according to several criteria; the weights (wi) show the relativeimportance of each criterion.

In the MATLAB code (see Fig.3.12) we defined the weights and values of the decisionvariables (x) for each criterion. We defined the objective functions (f1 to f5) corresponding to each criterion. For the cost-related criterion(f2), we used negative values to maximize cost reduction.

Then, we calculated the value of the multi-criteria function (f_x) by summing the weights of each objective function. The result indicates the overall performance level, taking into account all the criteria and the corresponding weights

3.3. Mathematical formulation of the multi-criteria equation of the generalized model for production flow analysis

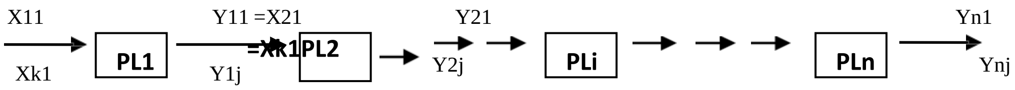
To this end, I formulate a multi-criteria equation with a conveniently chosen system of criteria for assessing the performance of manufacturing systems leading to a general mathematical model in which the accepted criteria are incorporated in the context of imposed technical conditions.

A correct and complete assessment of the performance of a manufacturing flow can only be made by considering all the criteria listed above and determining an overall performance index. Knowing the overall performance index makes it possible to choose the most appropriate way of increasing it through technical, technological or economic changes.

Defining the performance of a manufacturing flow

A manufacturing flow aims to produce a final product. For this, *n* work stations (WP) are required. For each workstation certain independent input variables are defined denoted by X_i, i =1, 2,... k and certain dependent output variables denoted by Y_e, e =1, 2, ... j. Between the input and outputvariables there are various correlations depending on the workstation defined as process functions. The output variables of one PL are input variables in the next PL. The definition of the correlation functions is determined according to the intended criterion and can betheoretical, inferred based on physical considerations or based on experimental results and are of the form [60]:

$$Y_{nj} = F_{PL1}\left(X_{n1}, X_{n2} \dots \dots \dots . X_{nj}\right) \tag{17}$$



(18)

For each *PL* workstation, an overall *IP* performance index similar to the technical level of the machines can be defined using the Von Neumann-Morgenstern utility principle in Cobb-Douglas production functions [61]:

$$IP_j = F_{PLj}\left(C_{P1,}\, C_{P2,} \dots \dots . C_{Pi}\right) \tag{19}$$

In order to be able to formally define the overall *IP* performance index we will assimilate the technical characteristics of a machine with the criteria for assessing the performance of a workstation (C_{pi}) (production efficiency, costs, product quality, T_{cy} cycle time, flexibility, energy consumed, etc.). It can be seen that in order to increase the overall performance index some criteria must have higher values (production efficiency, product quality, flexibility, etc. where $j=1$, 2, ...f) andsome lower values (costs, cycle time T_{cy}, energy consumed, etc. where $j=g$, ...i). The practical usefulness of the overall performance index *IP* is when it is used for the analysis of two manufacturing flows, one initially FFa and the other resulting from the first by making improvements FFb. Thus, the form of the performance index on the basis of which a decision to improve a manufacturing flow can be justified is:

$$IP_{jab} = \prod_{j=1,2,..f} \left({IP_{ja}}/{IP_{jb}} \right)^{\alpha_j} \times \prod_{j=g,..i} \left({IP_{jb}}/{IP_{ja}} \right)^{\alpha_j} \tag{20}$$

Where j = 1, 2, ...f for the criteria to be increasing and $j = g$, ... i for the criteria to be decreasing, and α_j is the influence weight of criterion j on IPj .

In this way, by relating the relative indices$\left({IP_{ja}}/{IP_{jb}} \right)$, dimensionless factors are obtained.

The exponentα_j can take values between 0 and 1. For a value of 0 it follows that the criterionis not important, and for a value of 1 the criterion is the only one that matters. It is recommended to exclude both situations. In the general version the relationship must be respected:

$$\sum_1^i \alpha_j = 1$$

The most important criterion for judging a manufacturing flow is *E-efficiency*. This is the ability of the manufacturing flow to produce a maximum number of parts in a given time; this criterion can be quantified by the production *rate* or the *feel of* the flow. In this case the performance of the manufacturing flow is:

$$PFE = Np$$

where Np is the number of pieces.

The *production cost* criterion Cp represents the ability of the manufacturing flow to produce a number of products in a given time at the lowest cost. This criterion can be quantified by estimating operating costs as follows:

$$PFCp = 1/Cp.$$

Product quality criterion Cc is the ability of the manufacturing flow to produce high quality products in accordance with the required specifications and standards; this criterion can be quantifiedby the level of compliance and the number of parts rejected NR during the production process:

$$PFCc = 1/NR.$$

Application:

Consider a manufacturing flow consisting of 3 workstations. At the end of the flow one product is produced every 5 minutes, so the flow rate is 5 with a production cost of 1000 lei. The average complaint per 100 products is 1.

In order to increase flow performance, it is decided to replace an operator at a workstation with a robot. In this variant, a product is produced every 4 minutes (the touch is 4) and the cost is reduced to 900 lei. The quality of the products increases with one complaint per 1000 products.

For the 3 criteria we will set the following priority exponent values according to the manufacturer's interests: $\propto_{1=}\ 0{,}4$, ,$\propto_{2=}\ 0{,}3\propto_{3=}\ 0{,}3$.

Compared to the initial version where the value is equal to 1, in the improved version the overall performance index will be:

$$IP = \left(4/_5\right)^{0,4} \times \left(1000/_{900}\right)^{0,3} \times \left(\frac{1/100}{1/_{1000}}\right)^{0,3} = \left(4/_5\right)^{0,4} \times \left(10/_9\right)^{0,3} \times \left(10/_1\right)^{0,3} = 1.88. \quad (21)$$

This means that by replacing the human operator at one workstation with a robot, the touchhas been reduced because some operations at the other two stations have been taken over by the robot, thus reducing cycle time, costs have been reduced and quality has increased. In this case, after setting the priority exponent values, the performance indicator increased from 1 to 1.88.

Compared to the other multi-criteria equations presented, the generalised model equation for the analysis of production flows proposed by the author has the advantage that it can be used as a basis for the decision to justify the modernisation of each workstation. This advantage derives from the fact that each time the initial performance indicator is compared with the one resulting from the proposed change for any workstation.

3.4. Conclusions on theoretical analysis and optimisation of manufacturing flows

Improving the quality of products and services cannot be achieved without optimising the manufacturing workflows involved in their operation. Modern practice requires improvement of production processes, as opposed to the old approaches which were based on improving outputs. The possibilities for improvement/optimisation of manufacturing flows are endless - according to the Asian concept or, optimisation through innovation - according to Western culture.

Optimising the logistics networks and manufacturing lines of each productivity-driven company has a significant impact on the performance and quality of the final product, with process monitoring and digitisation becoming priority actions for these sectors. Simulation of manufacturing flows is necessary because it helps to identify factors that penalize productionactivities and shows ways to optimize flows, processes, for the highest productivity.

Optimisation of manufacturing flows can be achieved using algorithms that allow minimising certain functions (e.g. resources, optimisation and control of manufacturing architectures), successively generating sets of variables, arriving at an optimal set.

From a theoretical point of view, the organisation of production can be defined as that form of organisation of basic production, characterised by the specialisation of workplaces in the execution of the operations necessary for the manufacture of a product or groups of products, by the locationof workplaces in the sequence of execution of operations and by the movement of products from one workplace to another by appropriate means, usually mechanised, on the basis of a pre-established operating tact.

It can be mentioned that the optimization of manufacturing flows based on a study related to modeling the process of structuring and optimizing information flows in industrial units constitutes aconsistent accumulation of data, information, projections, reasoning, involving different specialties, as well as the integration of different attitudes in strategic and operational management.

CHAPTER 4 - CONTRIBUTIONS ON IMPROVING PRODUCTION PROCESSES THROUGH SIMULATION

4. 1. Classification of simulation models and techniques; simulation models

4.1.1. ***According to the physical nature of the model elements***, they can be listed:

Physical models ;

Abstract models divided into:

- o *qualitative abstract models*;
- o *abstract quantitative models* divided into:
  - *deterministic models*;
  - *statistical models*;
  - *stochastic models*;
  - *fuzzy models*;
  - *mixed models*).

Hybrid models.

4.1.2. According to the mathematical nature of the relationships in the model they can be listed:

- o *Linear models* e;
- o *Nonlinear models*.

4.1.3. ***Depending on the nature of the evolution of the modelled system,*** they can be:

- o *Static models* ;
- o *Dynamic models*:
  - stable dynamic models;
  - dynamic models.

4.1.4. ***According to the object of the research*** they can be listed:

- o *Microeconomic models*;
- o *Models*.

4.1.5. ***According to the nature of the variables,*** they can be listed:

- o *Discrete models* ;
- o *Models continue* .

Simulation optimization of manufacturing flows can be applied in:

- optimal production planning, control and scheduling;
- analysis of statistical data and construction of empirical models from experimental results to obtain the most accurate representation of physical phenomena;
- optimal design of machines, machinery and plant design;
- the choice of location of a productive firm;
- planning maintenance and replacement of equipment to reduce running costs;
- stock control;
- optimal design of control systems.

Simulations are operations of a procedural nature using specialised software capable ofrepresenting the operation of a machine, system or phenomenon with the aid of a computer. The useof simulators for production processes aims at defining production operations, eliminating non- values, achieving the highest possible production volume in the shortest possible time at the lowest possible cost.

Simulation can be used both as an analytical tool to predict the effects of changes to an existing system and as a design tool to achieve the performance of new systems under different circumstances, and is used for the following purposes:

- for studying and experimenting with the internal actions of a complex system or subsystem;
- for informational, organisational and environmental changes that can be simulated, with influences on model behaviour observed;

- for checking analytical solutions.

Three types of models are distinguished for simulation:

1. Discrete or discontinuous patterns;

2. The patterns continue;

3. Combined models.

Simulating the location of workshop components

By simulating the location of the components of a workshop, it is intended to achieve the proposed objectives taking into account the number of machines and their type, the nature and size of the warehouses (storage, stores, feeding systems, storage areas, etc.), the nature and size of the handling system for parts, tools, semi-finished products and the amount of manpower required.

Simulating the operation of a workshop

Simulation allows good shop floor management by meeting manufacturing deadlines, assessing costs, reducing unfinished production, reducing scrap, etc.[52].

Simulating workshop management

This type of simulation allows the evaluation and comparison of different management strategies in order to adopt the most efficient solution based on the analysis of production planning, priority rules for products or technological variants, resource distribution strategies (machines, production lines, operators, etc.), product marketing campaigns.

The process of optimising and automating workshops has direct implications on the structure of modern industrial machinery by increasing the electronic and software elements, thus reducing the mechanical part of the machine by 25%.

Simulation optimisation of the cost-quality ratio

Keeping the company in the market for products and services is very important and can be achieved by addressing the concepts of simulation and production logistics. Thus, computerization reduces costs because it leads to a better understanding and management of material and informationflows, which play an important role in the coordination of a complex industrial system [53].

The information can be handled in the production simulation on three hierarchical levels:

- local level;
- level;
- central level.

4.2. Modelling and simulation of mechatronic systems

Solving problems with simulation techniques requires the use of interactive algorithms and well-defined steps to achieve the assumed goal; even if Monte Carlo methods differ, they follow thesame steps:

- definition of the variables to be studied;
- random generation of variable values;
- deterministic computing;
- aggregation of results.

The nine steps required to implement the Monte Carlo method [127]:

- development of the main question;
- creating representative equation models;
- design specific conditions;
- selecting parameter values;
- selecting the right software,;
- running simulations;
- creating matrices;
- evaluation of the statistical accuracy of the process;
- summary of results.

4.3. Simulation optimization research on the implementation of a robot cell

4.3.1. Mathematical modelling of the system

Modelling a system is based on the need to analyse it in order to identify and understand the relationships between its components, to estimate how it will operate under certain conditions (hypothetical stage and design stage).

A system is a collection of resources and procedures joined and regulated by interactions or interdependencies to perform a set of specific functions [79], oriented towards a common goal.
In terms of the industrial system, it is made up of the machines, component parts andworkers working on a processing or assembly line to complete a complex, high-quality product. Any system is influenced by changes that occur externally (a car company's system can be influenced externally by increasing or decreasing demands for a particular type of equipment).

The system has a fairly complex structure comprising elements of planning, specification, analysis, design, implementation, deployment, structure, behaviour, input data, output data.
By modelling a system, an abstract representation is attempted in order to artificially reproduce the existing system, thus being able to analyse the elements of the underlying system and predict its behaviour.

The purpose of modelling a system [81] is:

- the revelation of phenomena or processes taking place within the real system;
- mention the consequences or usefulness of different decision methods;
- description of the components or subsystems of the real system.

4.3.2. Optimisation through simulation

Implementing a cell robotic, in the postof processin g Balador 1-2 PA,has emerged as aresultofnew technologies (Industry 4 .0) and due to the need to improve quality and make savings (by replacing the operator servicing the threeprocessing plants).
The processing operations concerned are:

- balador external damping;
- deburring;
- shaking.

During the working time of the 3 machines, which were serviced by one operator, the operational efficiency was quite low (approx. 30% - average on 3 shifts - see Fig.4.1).

SINTEZA STUDIU TIMPI SET BALADORI 1/2 PA																	
Nr.Op	Denumire Op.	Tdth	Tcy	Tmo	To	TomDT	Tom	Tuo	Tuo+TSP	Tio	Nr.Mas	Cadenta orara		Cdte. MDT	A 10	Tuo+TSP	Arg.
0	1	2	3	4	5	6	7	8	9	10	11	nom	max				
170	FREZ DANTURA(1/2)	0,67	0,67	0,687	0,698	0,707	0,734	0,1013	0,0547	0,5967	1,0	82	90	(2)1H/6M	0,055		7%
190	DANTURARE(1/2)	0,664	0,664	0,666	0,674	0,683	0,71	0,084	0,091	0,59	1,0	85	90				
195	SANFRENARE(1/2)	0,284	0,284	0,285	0,289	0,295	0,306	0,09	0,098	0,199	1,0	196	211				
200	SEVARUIRE(1/2)	0,621	0,621	0,624	0,634	0,644	0,67	0,119	0,128	0,515	1,0	90	97				
CDPM	190+195+200(1/2)	0,664	0,664	0,67	0,694	0,716	0,744	0,393	0,424	0,301	1,0	81	90		0,424		52%
210	SPALARE(1/2+3/4+5/6)	0,4	0,4	0,4	0,4	0,404	0,42	0	0	0,4	1,0	143	150				0%
	TOTAL GEN.	2,639	2,639	2,662	2,695	2,733	2,84	0,3943	0,3717	2,3007	5			2H/Ech.	0,479		30%

Fig. 4.1 – Tcy Machining Operation Values

The operations performed in the processing cell are:

- external grooving - grooving operation, by the method of rolling with a module auger mill (LIBHERR machine);
- deburring - the operation of removing burrs resulting during the grooving operation by milling (WERA machine);
- shaving - the operation of fine smoothing of the flanks of unscraped gear wheels by mechanised scraping (SICMAT).

With the stock secured, the parts are transferred to the area from where they are picked up by the robot arm using a conveyor. From here the specific operations of the machining cell can be listed:

1. part pickup on the part input conveyor;
2. loading the part into the LIBHERR machine;
3. unloading the workpiece from the LIEBHERR machine;
4. unloading the workpiece from the WERA machine (deburring operation);
5. loading the unprocessed part into the WERA machine;
6. unloading of workpiece from SICMAT machine
7. loading the unprocessed part into the SICMAT machine;
8. part deposition on the output conveyor by the robot;
9. if there is a request to control the part then the robot will take the part to the control and wait for its validation;
10. if the validated part is OK the robot will continue the unload/load cycle.

4.3.3. Validation of the mathematical model through experimental research

In order to meet all the conditions of operation in good quality and safety conditions, simulations were necessary to identify all the necessary modifications to implement a robot to serve the 3 pr oce ssing machines.

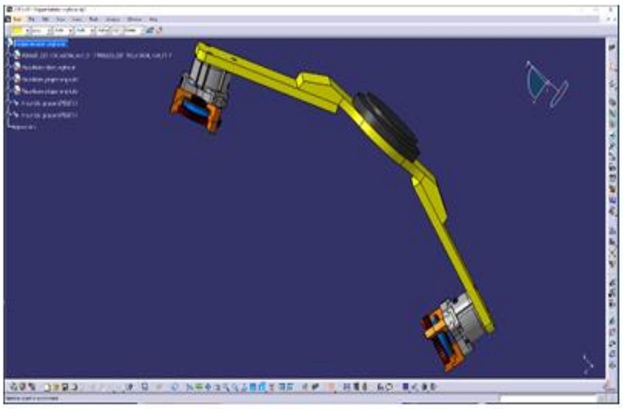


Fig. 4.4 – Gripper Representation

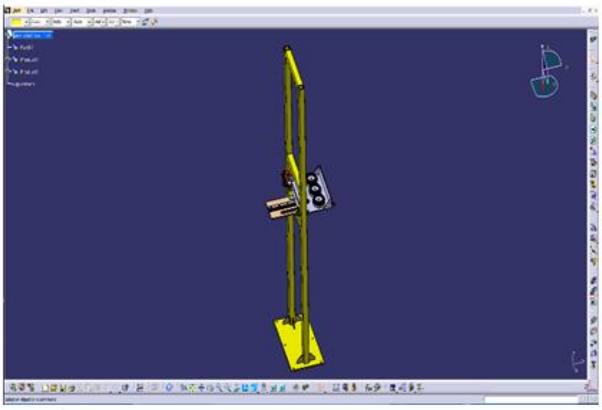


Fig. 4.5 – Control Post Representation

In order to implement the robot to serve the 3 processing units, simulations were necessary to establish all the operating conditions:

- 2 conveyors have been designed for the transfer of parts;
- A part clamping assembly has been designed for part clamping;
- for mounting the part clamp assembly to the robot arm, a mounting plate.The chosen model is also cost-efficient, generating high uptime andlow production costs.

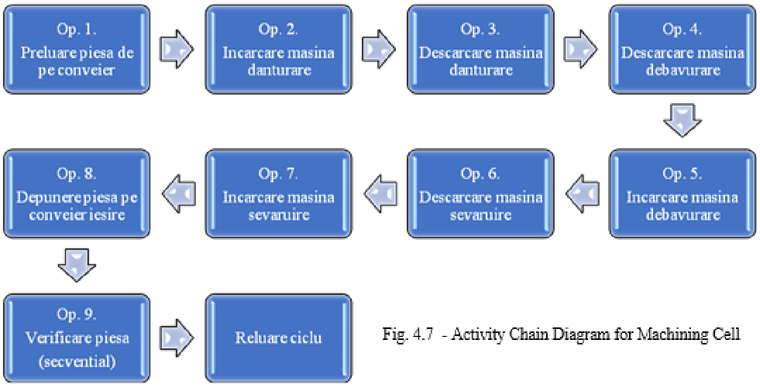


Fig. 4.7 - Activity Chain Diagram for Machining Cell

The investment for the robotisation of the processing cell amounts to €27k (€18.5k IRB 6620 robot; €8.5k trade items required for commissioning. The cost of one operator is estimated at 17 k€/year, resulting in a two-year payback on the investment - a feasible investment (processing cell operating mode see Fig.4.7).

Digital simulation/modelling is a widely used method and an important tool in the analysis andsolution of actions involving human activities, but it requires a thorough study, rigorous planning and detailed design of all actions to be performed in reality (see Fig.4.8).

The advantages of systems used in simulation/modelling are thespeed with which they solve requirements, the flexibility
And reconfigurability; manufacturing systems can be defined as complex automated systems due to the use of monitoring and control software and their efficiency can be seen from the start of commissioning.

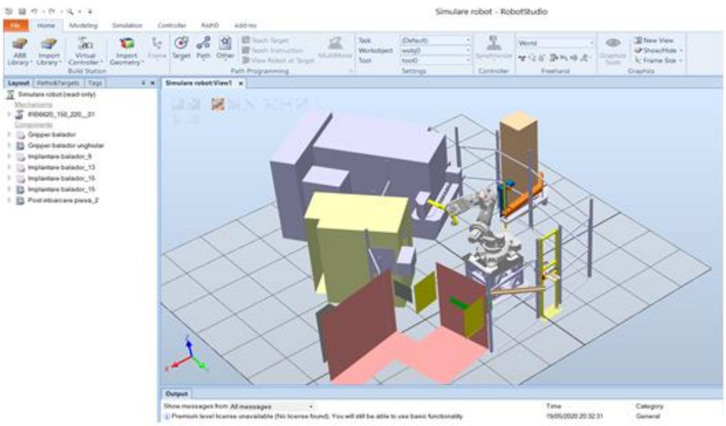


Fig. 4.8 – Simulation of Robotic Operations

By implementing a robotic cell in the Balador 1-2 PA processing station, the following significant gains were highlighted:

- increased operational efficiency - before the implementation of the robot cell, operational efficiency was limited by human interaction and operator travel times;
- reducing human error - manual operations are susceptible to human error, which can have a significant impact on the quality and efficiency of production processes;
- Optimisation of production times - robotic operations are characterised by consistency and precision, resulting in optimised production times;
- Increased flexibility - the robotic cell allows adaptability to different operations, which means it can be used for a variety of products and processing operations;
- reduced operational costs - by replacing manual operations with robotic ones, operational costs related to labour and errors have been reduced;
- Improved monitoring and control - with the robotic cell, monitoring and control of production processes has become more advanced and precise;
- reducing downtime - the introduction of the AGV for parts supply and the updating of the buffer stock have led to the elimination of downtime between operations and to a continuous and efficient workflow.

Thus, by optimising processing operations through robotic technology, it has beendemonstrated that the implementation of new technologies within Industry 4.0 can bring significant benefits to the performance of production processes.

CHAPTER 5 - EXPERIMENTAL RESEARCH ON INCREASING THE PERFORMANCE OF THE MANUFACTURINGFLOW THROUGH ROBOTISATION

The Bodywork Department is part of the Vehicle Manufacturing Plant, the objective being to spot weld sheet metal sub-assemblies to make vehicle bodies.

5.1. Elementary unit presentation

Spot welding, specific to the automotive industry, is a welding process that results in solid anddurable joints between metal components. Requirements can vary depending on the type of material, its thickness and the strength requirements imposed by current standards.

The elementary work unit "Duster rear unit" (see Fig.5.6) is part of the Bodywork department and consists of 33 manual stations (shaping/welding operations of sheet metal elements) for the Duster

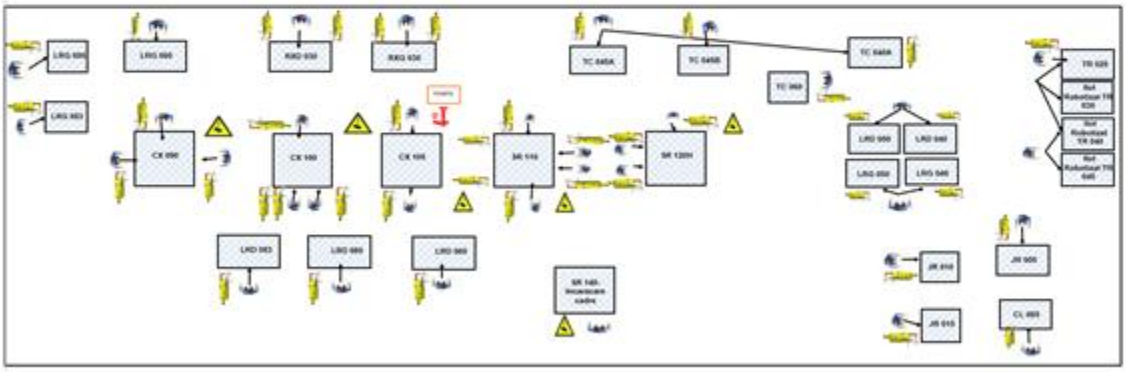


Fig. 5.6 – Duster Rear Unit Mapping

vehicle.

Operator substitution for welding operations in the automotive industry could be an effective strategy and could significantly increase the efficiency and consistency of the welding process.

This wouldrequire the followingstrategies:

- the use of robots or automated machines in the welding process, ensuring high precision and quality;
- shielded arc welding (MIG/MAG) - the automated use of a welding gun that is fed with welding wire and shielding gas;
- Electric resistance welding - involves the use of special equipment that applies pressure and electric current through the electrodes, resulting in a quality weld;
- use of welding technology with recording - recording of parameters and efficient management of anomalies occurring in the welding process.

5.2. Identify changes replacing manual operations with robotic operations

Productivity analysis - the productivity of manual operations should be compared with that ofrobotic operations; it is necessary to

Calculate the time required to complete each welding operation and compare the results [3]. For this analysis from the outset there is an advantage to robotic operations due to the speed andconsistency of robotic operations.

Time required to perform a welding operation

- working capacity ofrobotic workstations ;
- Comparison of production capacity;
- Efficiency evaluation.

Quality analysis - must be evaluated the quality of products obtained from manual and robotic operations (uniformity and accuracy of welds,reduction of defects and elimination of human error):

- Compliance with welding specifications ;
- Uniformity and consistency;
- Detecting defects and damage;
- Error reduction ;
- Monitoring and control of the process;
- Improve documentation and records.

On the vertical axis (see Fig.5.7) we have the quality indicator (DPU OFF), which reflects the level of quality or performance in the organisation. The indicator is a measure of compliance with standards, process efficiency or customer satisfaction, depending on the specific context.

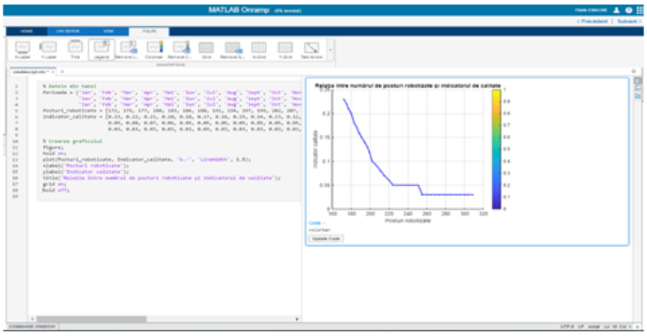


Fig. 5.7 – Multicriteria Quality Indicator Representation

The line formed by the dots on the graph shows the trend of the relationship and provides a clear view of the positive influence of robotisation on the quality indicator.

Note:

Tcy is reduced from an average of 56 sec/shift (the 33 manual shifts) to 42 sec/ robotic shift.

Cost analysis - costs for manual operations and robotic operations (labour costs, initial investmentin robots, etc.) should be calculated.

Salary costs for 99 operators (3 teams):

17.000€/year x 99 operators = 1.683.000

€/year Cost of purchasing robots (15 pcs) :

50.000 x 15 = 750.000 €

Maintenance costs per year for robots (maintenance cost/robot in the first 4 years =2.000€):

15 x 2.000 = 30 .000 €/year

Annual savings: (Operator salary costs - Robot and maintenance costs):1.683.000 - (750.000 / 4) + 2000 = 1.497.500 €

The graph (see Fig.5.8) represents the relationship between the number of robotic jobs and the decrease in HS (overtime required to perform cadence due to certain human errors or longer cycle times in manual operations).

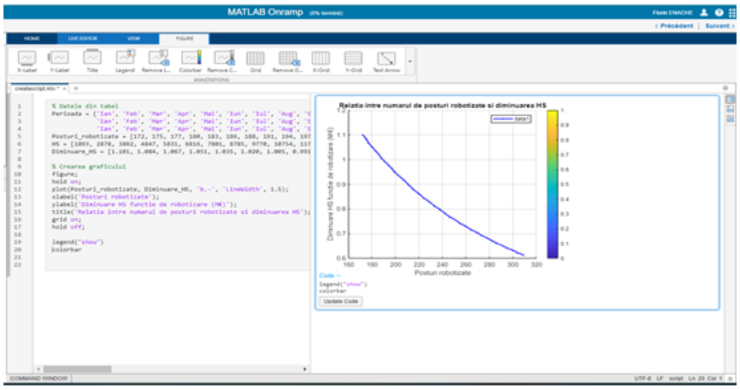


Fig. 5.8 – Multicriteria Cost Equation Representation (Reducing HS)

On the horizontal axis we have the number of robotic stations, on the vertical axis the amount provided for overtime pay to meet the manufacturing schedule. This graph allows us to visualise the relationship between the number of robotic posts and the decreasein HS, showing that an increase in the number of robotic posts leads to a decrease in HS (gives a clear view of theinfluence of robotic posts in the cost analysis).

Occupational ***safety and health analysis*** - the risks associated with manual operations must beassessed and the benefits in terms of safety and security identified through the use of robots, risks ofinjury, exposure to hazardous substances or various radiations, ergonomic conditions.

The first graph shows the decrease in the number of manual posts according to the reference period (the period is January 2021 - December 2023); on the horizontal axis we have the months, onthe vertical axis we have the difference from the initial number of manual posts.
The second graph represents the change in the number of minor accidents according to the reference period (January 2021 - December 2023); on the X-axis we have the reference period, on the Y-axis we have the number of minor accidents.

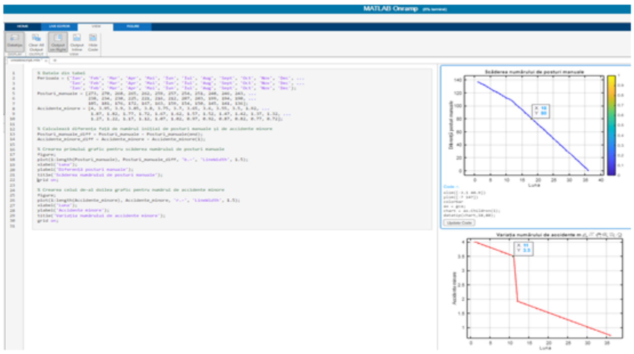


Fig. 5.9 – Multicriteria Equation for Occupational Safety

The two graphs (see Fig.5.9) allow us to visualise the evolution of the decrease in the number of manual posts and the variation in the number of minor accidents, giving us a clearer perspective on the positive influence of the increase in the number of robotic posts.

Flexibility and adaptability analysis - assessing the ability of robotic operations to adapt to changes in the production process (how long it takes and how much it costs to reprogram and reconfigure robots to work different models or to meet new requirements) [10].

Workforce impact analysis - the impact of replacing manual operations with robotic operations on the existing workforce should be assessed; the possibility of redeployment of redundant staff, the need for additional training and the social repercussions.

5.3. Manufacturing flow design with robotic operations

For any change in production flows, a significant number of analyses are required to eliminate all identified risks as well as possible unknown situations at the time of the analyses (Monte Carlo method) [1].
Thus, the following were analysed[2]:

- duration of each operation and order of fitting;
- the complexity and specific requirementsof each operation;
- establishing the correct order of operations to minimise travel time and ensure efficient flow;
- synchronisation between robots.

5.4. Implementation of manufacturing workflow with robotic operations

The implementation of robotic operations in the manufacturing line flow leads to an increase intheproduction rate and overall efficiency of the Body Shop department; the adoption of robotic operations is an innovative and modern solution that will significantly improve the manufacturing processand bring competitive results to the department [6].
The implementation solution consists of 15 robots specialised in welding car bodies.

The robotic system setup is an essential component of the manufacturing flow with robotic operations, involving a number of issues and decisions that need to be made to ensure optimal operation of the robotic system [11].
I will list some of the steps in setting up the robotic system:

- Location.
- Programming and configuring robots.
- System integration.

Robot cell design - involves planning and configuring the workspace to ensure efficientinteraction between robots, workpieces and human operators.

- Requirements and workflow assessment;
- Work layout design;
- Define the location and installation of ancillary equipment;
- Setting up the safety zone of protection systems;
- Robot integration and design.

Integrating robots into the manufacturing flow - The steps in this section are :

- Operational sequence;
- Interaction with human operators;
- Integration with equipment and systems;
- Timing and coordination of movements;
- Testing and validation.

Parameters of robotic operations - the parameters of robotic operations are specified for eachwelding station (cycle time, working speed of the robots and precision achieved in the welding process):

- Travel speed.
- Force and pressure parameters;
- Accuracy and repeatability;
- Cycle time (Tcy);
- Safety parameters.

Robotic operations scheduling and control is the process of creating instructions and managingrobots within the manufacturing flow and focuses on how robotic operations are scheduled, controlled and monitored.

As stages of programming I can list :

- Programming robots;
- Interaction with human operators;
- Robot control and synchronisation;
- Monitoring and recording data;
- Updating and improving robotic programmes.

System testing and optimisation (most important aspects) :

- Initial system testing;
- Parameter optimization;
- Monitoring system performance.

Staff training:

- Identify training needs;
- Development of the training programme;
- Theoretical training;
- Practical training;
- Skills assessment and certification.
- Continuous updating of training.

The integration of the system into the existing infrastructure is an important step in the successful implementation of the robotic manufacturing workflow, with the new operations replacing a significant number of manual operations (33 stations served by human operators).

The steps required to implement the robotic system are :

- Infrastructure assessment;
- Layout planning;
- Installation of power supply infrastructure;.
- Control system integration;

- Ensuring safety and security;
- Integration testing and verification;
- Documentation and maintenance of infrastructure.

The evaluation of results and benefits provides a detailed analysis of the results achieved:

- Measuring efficiency;
- Quality;
- Reducing errors and;
- Improvement;
- Productivity and production capacity.

Following the completion of all the steps briefly described in the step "Implementation of the manufacturing flow with robotic operations", 15 robots were deployed and commissioned intheworkshop.

Description of operations:

- At station CX05, robot **A0** picks up the frame (made up of the side rails, the central cross beam andthe paraclear) and deposits it in station CX10 ;
- At station CX10, robots **D1** and **D2** weld ;
- The **E0** robot picks up the CX10 from the post and welds it into a clamp on the ground and then deposits theworkpiece into the CX20;
- In station CX20, robots **F1** and **F2** weld ;
- Robot **G0** picks up the workpiece and deposits it in SR10 where it is joined to the boards (rearboard rear side / rear board front side) which are loaded in station SR05;
- Robot **M0** takes the welded assembly and transfers it to robot **L4** for the mastication operation;
- After mastication, robot M0 lays the boards after which robots **L1**, **L2**, **L5** and **L6** weld;
- At the end of the operations the M0 robot picks up the piece, welds it to a ground clamp anddeposits it in the SR20 where the skirting is married;
- At the end of the operation, the skirt is brought by the **Q0** robot and loaded by the human operator atSR20 ;
- The **V0** robot takes the piece from the SR20, welds it to the ground and deposits it in the SR30.

5.5. Monitoring andoptimisation of robotic manufacturing flow

After implementing a robotic production flow, continuous monitoring and evaluation are necessary to ensure the system is performing efficiently and effectively (see Fig.5.10). Here are some important steps in monitoring and evaluating the performance of a robotic manufacturing flow:

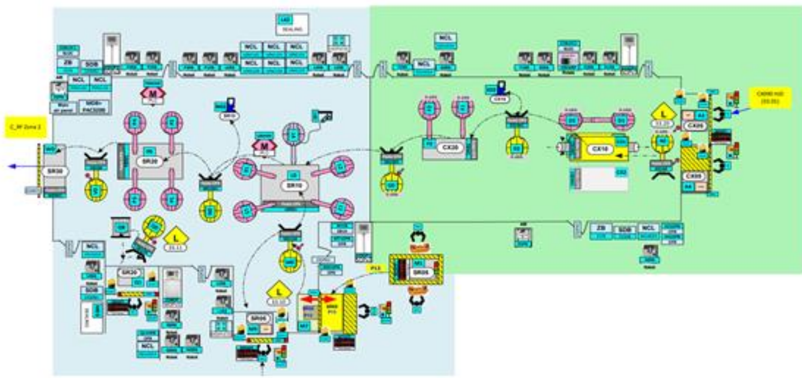


Fig. 5.10 – Robotic Flow Implementation

- Data Collection;
- Collect relevant data related to the robotic manufacturing process. This includes data on cycle times, quality metrics, error rates, and other relevant performance indicators.
- Data Analysis: Analyze the collected data to identify trends, patterns, and areas that require improvement. Data analysis can provide insights into the performance of the robotic system.
- Identification of Weak Points and Improvement Opportunities:
- Identify areas where the robotic manufacturing flow may be underperforming or where there are opportunities for improvement. This can include issues related to cycle times, quality, or efficiency.
- Feedback from the Operations Team;

- Gather feedback from the team operating the robotic system. They may have valuable insights into the day-to-day performance and can identify areas that need attention.
- Collaboration between Teams:Promote collaboration between different teams involved in the robotic manufacturing process, including engineers, operators, and maintenance teams. Effective communication can lead to better problem-solving and optimization.
- Periodic Reevaluation:

5.6. Assessing the increase in manufacturing flow performance through robotisation

The assessment of the level of increase in manufacturing flow performance (in this case) may involve several indicators and assessment methods, as follows:

- Cycle time (Tcy) If the cycle time has decreased, it follows that the investment has been beneficial.
- Production efficiency - measure production efficiency by comparing production volume before and after the implementation of robotics.
- Product quality - whether there is a significant reduction in defects or an improvement inproduct uniformity and consistency.
- Decrease human error - monitor and compare error rates before and after robotics implementation to assess improvement.
- Operating costs - whether these fall significantly or whether the efficiency of the workincreases in relation to the costs involved.
- Employee feedback - whether performance improvement is observed (decreased physicaleffort, increased job satisfaction).

Multicriteria equation on assessing the level of performance growth:

$$\text{minimizes } f(x) = (f1(x), f2(x), ..., fn(x)) \tag{23}$$

or

$$\text{maximizes } f(x) = (f1(x), f2(x), ..., fn(x)) \tag{24}$$

where:
- f(x) is the vector of objectives or performance criteria;
- x represents the decision variables or parameters of the system or process.

Returning to our case, with the robotization of the 33 manual stations, we constructed the multi-criteria equation:

- ***Criterion 1*** - 50% reduction in the number of manual workstations (replacing them with robotic workstations); measures the benefit of replacing manual workstations with robotic workstations, representing a significant change in workforce training and can contribute to increased efficiency and productivity.
- ***Criterion 2*** - costs of purchasing and implementing robotic workstations. This criterion reflects the costs associated with acquiring and deploying robotic workstations; the lower the costs, the more favourable the decision to robotise.
- ***Criterion 3*** - productivity resulting from the replacement of manual and robotic workstations. Measures the increase in productivity due to the use of robotic jobs instead of manual ones.
- ***Criterion 4*** - quality of the products obtained by replacing the manual stations with robotic ones.
- ***criterion 5*** - impact of technological change. Assesses the impact of technology change through increased automation.

The weights associated with each component are:
w1 - increasing workforce skills ;
w2 - replacement of machines with more efficient ones
; w3 - automation ;w4 - robotisation ;
w5 - changing technology.
After replacing the specific values :

f1(x) = 50% (50% reduction in the number of manual posts) = **0.5**

f2(x) = cost of purchasing and implementing 15 robotic stations = 15 * (50 + 2k€/year) =15 *(0.052M€) = **0.780** M€

f3(x) = Productivity resulting from replacing manual with robotic shifts = (56 sec/ manualshift) / (42 sec/ robotic shift) = **1.3333**

f4(x) = the quality of the products obtained from the use of robotic stations (DPU OFF indicator, measuring the number of defects reworked outside the manufacturing flow x 100/ numberof assembled bodies, the target is to decrease from 0.25% to 0.15% after the introduction of robotic operations) = **0.99975** (initial value scaled backwards).

F5(x) = impact of technology change = **0.42** (initial value scaled directly) Afterapplying the appropriate weights the result is:

f(x)1*0.05)+(2*0.780M€=+(3*1.3333)+(4*0.99975)+(5*0.42) (25)

f(x) = 0.5+1.560M€+ 3.9999 + 3.999 + 2.1 = 1.560M€+10.5999 = 1.560M€

After applying the multi-criteria equation with the specific values and weights assigned to each criterion, we obtained a high value, resulting that the implementation of robotization brings significant benefits in terms of reduction of manual work stations, costs, increased productivity and product quality, as well as the impact of technology change.

On the horizontal axis of the diagram are the labels of the criteria: "Increasing workforce training", "Replacing machinery", "Automation", "Robotisation", and "Technology change" and represent the specific aspects considered in the assessment of the robot cell performance.

The bar chart (see Fig.5.11) gives us a visual perspective on the relative importance of each criterion and helps us to understand how it contributes to the overall assessment of the performance of the system or process under analysis.

After experimental research on the process of robotisation of a part of the manual operation stations I can mention the following:

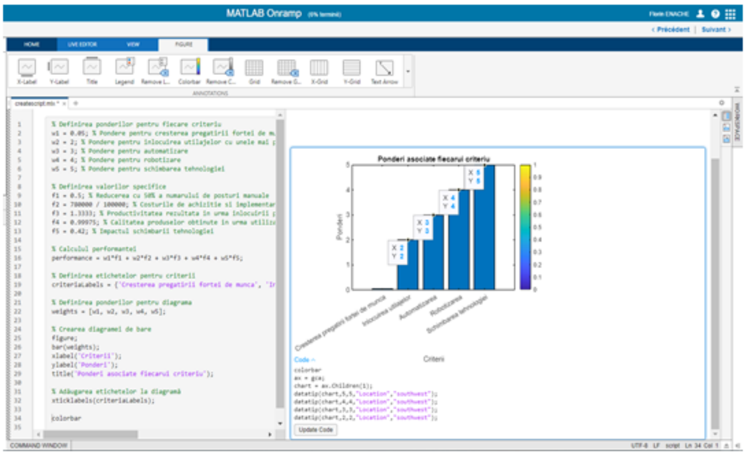


Fig. 5.11 – Multicriteria Performance Evaluation Representation

- Cost reduction - automation of the production process through robotic stations can lead to a reduction in significant reduction in productioncosts in the long term, withefficiency due to reduced human error and lower labour costs;
- Increased work efficiency and productivity - the use of robotic stations decreases cycle times for almost all operations, achieving higher production with maximum efficiency; all robotic operations are performed with higher precision than manual ones.
- Impact on the workforce -

The robotisation of some manual operations can have a significant impact on the current workforce requiring employer support for conversion assistance for the jobs concerned.

Automating/ robotising some manual operations shows that there is a significant gain in termsof quality and productivity of work, but this can only be done after detailed assessments and proper planning to successfully make the transition and maximise the benefits of this change.

CHAPTER 6 - FINAL CONCLUSIONS AND PERSONAL CONTRIBUTIONS

6.1. General conclusions

The paper addressed various aspects of performance improvement in the context of manufacturing processes and provided a comprehensive perspective on how different technologies and methods can contribute to increased efficiency and quality in manufacturing.

In a changing business environment, Agile was presented as an essential approach to managing requirements in the manufacturing industry. It was stressed that the flexibility and adaptability offered by the Agile method are crucial in the development and implementation of digitisation and automation solutions. This approach enables organisations to respond quickly to market changes and optimise their processes to achieve superior performance.

In terms of analysis and optimization of production processes, the paper highlighted the importance of various methods and approaches such as Lean Manufacturing, Six Sigma, Kaizen, andothers. These methods aim to identify and eliminate unnecessary activities, reduce defects and optimise workflow to improve efficiency and productivity. The importance of flexible simulation and optimization analysis of cellular manufacturing processes to achieve more efficient and flexible production was also emphasized.

The importance of production management has been highlighted in several chapters, highlighting the crucial role of production planning and scheduling, quality control and supply chain management in achieving optimal performance of production processes. The implementation of methods such as Value Stream Mapping and the Toyota Production System have brought to the forefront the elimination of unnecessary activities and the improvement of workflows.

The importance of continuous monitoring and control of production processes using SCADA systems, Big Data analysis and IoT solutions was also highlighted. These technologies enable real-time data collection and analysis, helping to identify trends and deviations in order to keep process performance at optimal levels.

One of the major conclusions of the paper is related to the positive impact of robotics in production processes. Through the implementation of robotic cells, significant gains have been achieved in terms of operational efficiency, reduced human errors, optimised production times, increased product quality and increased flexibility. This approach has demonstrated thatrobotic technology canbring significant benefits to the efficiency and performance of production processes.

In conclusion, the paper highlights that improving the performance of production processes is critical to the success of industrial organisations. By applying the right methods, technologies and approaches, increased efficiency, quality and competitiveness can be achieved in the production environment. It is clear that an integrated approach, openness to innovation and continuous improvements are essential to meet the changing demands of the market and to achieve superior performance in production processes.

The objectives are the paths the researcher will follow in the work to achieve the desired results. In the case of this work, the objectives were set in accordance with the need to address and solve problems in the sphere of production process optimization.

These objectives are solid guides for the direction and structure of the whole work:

- ***Identification of current issues in the field of process optimisation*** - the first essential step is to analyse the current state of research and identify challenges and shortcomings in process optimisation. This objective focuses on highlighting the need and importance of the work, motivating future investigation;

- ***Exploring modern manufacturing technologies*** - this objective aims to provide a detailed understanding of modern technologies with a focus on Agile and Design Thinking principles. It aims to identify how these technologies can help to optimise manufacturing processes and increase performance;
- ***process analysis and modelling using AGILE*** - this objective aims to explore the ways in which Agile concepts can be applied to identify, model and optimise production processes. Production systems, manufacturing flows andassociated key concepts are examined, providing a sound basis for further analysis;
- ***examining AGILE methods for improving the performance of production processes*** - this objective focuses on evaluating AGILE methods in the context of improving the performance of production processes. The advantages and potential limitations of applying these methods are explored, providing a critical perspective on their effectiveness;
- ***creating a theoretical basis for process analysis and optimisation*** - with this objective we have developed a sound theoretical basis for the analysis and optimisation of production processes. Fundamental concepts, mathematical modelling methods and issues related to multi-criteria optimisation were examined, providing the necessary tools for further research;
- ***investigating the impact of simulation on process improvement*** - this objective aimed to analyse the role of simulation in improving production processes. I studied various simulation models and techniques, focusing on practical cases and case studies related to the implementation and optimization of robot cells;
- ***experimental research on automation through robotics*** - this objective focused on experimental research on automation through robotics. The results and findings from the application of robotics in manufacturing processes were explored, providing relevant evidence and insights.

In a synthetic way, the formulation of the thesis objectives indicates that the paper aims to explore and analyse methodologies and techniques for the optimisation of production processes, with a focus on the use of Agile, Design Thinking and robotics technologies. These objectives represent the research paths I have followed to contribute to the development of knowledge and practices in this field.

6.2. Personal contributions

After investigating multi-criteria equations from different angles and identifying innovativeways to address the complexity of manufacturing processes, we proposed a new theoretically based formula that is a significant contribution to the field of multi-criteria equations in that it theoretically justifies any change in the technological flow by giving a measure of the increase in the performance of manufacturing processes compared to the initial situation. It is aessential component of complex analysis and optimisation of manufacturing processes.

Personal contributions in this area include:

- <u>Development and adaptation of multi-criteria equations</u> - we have developed and adapted multi-criteria equations to assess the efficiency, quality and performance of production processes from several perspectives. This approach has facilitated a deeper understanding of the implications of different criteria on production process performance
- <u>analysis and comparison of multi-criteria methods</u> - we have carried out athorough analysis and comparison of various multi-criteria methods to assess which of them are most appropriate for the production processes specified in the paper. This evaluation allowed to identify the strengths and limitations of each method;
- <u>Applying multi-criteria equations in a specific context</u> - we have applied multi-criteria equations in the context of the production processes presented in the paper, helping to identify optimal solutions to complex problems such as resource, cost and quality optimisation;
- <u>we have devised a new form of multi-criteria equation</u> that forms the theoretical basis for production flow optimisation decisions;
- <u>analysis of results and interpretation</u> - we analysed the results obtained by applying the multi-criteria equations and interpreted the implications of these results on the performance of the production.

This step added a valuable dimension to understanding the impact of equations onoperational decisions.
- Validation of theoretical hypotheses through experimental research in automation through robotics.

6.3. Further research directions

Further research directions in the field of multi-criteria equations include:
- exploring new criteria - introducing new criteria for assessing the performance of production processes to include sustainability, environmental or social impact aspects;
- Adapting to Industry 4.0 - investigating how multi-criteria equations can be adapted to address the challenges and opportunities brought by Industry 4.0;
- Robust analysis - exploring robust analysis methods to assess the sensitivity of multi-criteria equations to variations in process parameters;
- Hybrid model development - investigating the possibility of developing hybrid models that combine several multi-criteria methods to obtain more comprehensive and accurate results;
- Extension to large datasets - applying multi-criteria equations on larger and more complex datasets to evaluate performance and optimization in realistic scenarios;

Through these personal contributions and further research directions, the paper provides a solid foundation for the development and continuous improvement of multi-criteria equations in the field of production processes, contributing to a deeper understanding of the complex and interrelated aspects of this discipline.

6.4. Exploitation of research results

The research done on the development of a generalised model for the analysis of production flows, with application in any industrial field, has been exploited in this way:

During the training period, a number of 5 scientific reports were carried out and defended within the Doctoral School of Engineering and Management of Technological Systems, in relation tothecurrent state of research in this field, analyses on the identification and application of significant gains in manufacturing lines (increasing product quality, decreasing manufacturing costs, improving ergonomics and safety at workstations, reducing maintenance costs, etc.) from a theoretical and experimental point of view.

Following the research carried out during the thesis development I disseminated the resultsby publishing the following articles in peer-reviewed journals:

1. Florin Enache, 2019, "Continuous growth of productivity- based performance of the organisation"/ Editura Academiei Oamenilor de Stiinta din Romania/ Proceedings/ Vol.11 no1/2019;
2. Florin Enache, Stefan Velicu, 2020, "Particularities of implementing industry 4.0 concept in the automotive industry"/ ICMAS/ Journal Proceeding in Manufacturing Systems/ Vol.15, Issue 4, 2020
3. Mihai Agud, Florin Enache, Ștefan Velicu, Mihai-Stelian Hagiescu, Cristian Paunescu/ 2023/ "Functional optimization of an air car by modeling and simulation" / SLS&OPTIROB2023 / International Journal of Modeling and Optimization (*IJMO*);
4. Florin Enache, Mihai AGUD, Stefan VELICU, Anisoara CORABIERU/ 2023/ Enhancingspeed regulation in pneumatic systems with electric flow control valves/ InnovativeManufacturing Engineering & Energy

I would like to thank the management and my colleagues at Automobile Dacia S.A. fromwhom I received a lot of documents, ideas for improvement and feedback on many questions that arose during the years of study.

BIBLIOGRAPHY

[1] Ahern, K. R., Harford, J. (2014), "The Importance of Industry Links in Merger Waves", Journal of Finance, Vol. 69, No.2, pp. 527-576.

[2] Ahuja, G. (2000), "Collaboration networks, structural holes, and innovation: a longitudinal study", Administrative Science Quarterly, Vol. 45, pp. 425-455.

[6] Beck, Kent "Embracing Change with Extreme programming". Computer (Volume:32, Issue: 10, October 1999: 70-77.

[10] Carol Schnakovszky, ,,Modeling and monitoring of logistic activities in production systems", EdituraTehnică-Info, Chișinău, 2000 (60,63).

[11] Chopra, S.,&Meindl, P. (2015), Supply Chain Management: Strategy, Planning, and Operation. Pearson. Coyle, J.J., Novack, R.A., Gibson, B.,&Bardi, E.J. (2016). Transportation: ASupply Chain Perspective. Cengage Learning.

[James P. Womack , Daniel T. Jones - Lean Thinking: Banish Waste and Create Wealth in Your Corporation, FREE PRESS A Division of Simon&Schuster, First Free Press Edition 2003.

[52] Kent M. Beck, Beedle, Mike; Bennekum, Arie van; Cockburn, Alistair; Cunningham, Ward; Fowler, Martin; Grenning, James; Highsmith, Jim; Hunt, Andy; Jeffries, Ron; Kern, Jon; Marick, Brian; Martin, R. C.; Mellor, Steve J.; Schwaber, Ken; Sutherland, Jeff; Thomas, Dave. "Manifesto for Agile Software Development" (https://agilemanifesto.org/principles.html).

[53] Krajewski, L.J., Ritzman, L.P., & Malhotra, M.K (2012) Operations Management: Processesand Supply Chain. Pearson, NewYork.

[60] Liu, X., W. Zhang, R. Radhakrishnan, and Y. Tu. 2008. "Manufacturing Perspective of Enterprise Application Integration: The State of the Art Review." *International Journal of Production Research* 46 (16): 4567-4596.

[66] Maier C., Nicoai M., Banu M., Totolici S., Ghiță E., ,,Modern Manufacturing Concepts. Justin time", Cartea Universitară Publishing House, 2006.

[73] Nahmias, S. (2015). Production and Operations Analysis. McGraw-Hill Education, NewYork.

[79] Parmenter, D. (2007) Key performance indicators. 1st. ed.New Jersey, United States: JohnWiley & Sons.

[81] Paynter, H.M. (1961). Analysis and design of engineering systems, MIT Press, Cambridge, Massachusets.

[89] Rongier et al. (2010). Towards performance measurement system to Control Disaster Response. Collaborative Networks for Sustainable World. Berlin, Heidelberg, Germany: Springer.