CONTRIBUTIONS ON ESTABLISHING THE IMPLEMENTATION PATHWAY OF THE INDUSTRY 4.0 CONCEPT IN SMALL AND MEDIUM SIZED COMPANIES

PhD Thesis - Abstract
for obtaining the scientific title of Doctor at
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The way today's society has developed has its origins in several cycles of industrial revolutions. The progress brought about by these revolutions has allowed industrial technologies to become globalized over time, resulting in the development of an increasingly branched and interconnected system of economic production. In recent times, digital transformation has had an increasing impact on production methods, and we can now speak of a digital age of industrial technology.

In this context, the thesis aims to analyze the stage a Romanian firm is at in terms of implementing the Industry 4.0 concept, the so-called maturity of the firm, and to propose a coherent path to follow for the implementation of this concept depending on the readiness and potential of the firm. For this reason, the study aims to analyze how Romanian firms, partners of the analyzed firm, are prepared for the transformation imposed by the Industry 4.0 system and their willingness to collaborate in the new development logic.

The opportunity of the research conducted lies in the lack of information on how Romanian firms are approaching the fourth industrial revolution and what stage they are at in implementing the transformations imposed by this revolution. Globalization implies that firms have to adapt and make their systems and working methods compatible, which is why it is important to have a picture of Romanian firms in the global context, but especially in the regional context. The lack of specific regulations or national programs to encourage firms to adopt the Industry 4.0 concept, as well as the lack of successful models, if they exist, makes this study all the more important.

To determine the firm's position in the national and international context and to establish a coherent path for the implementation of Industry 4.0, we defined the following objectives of the thesis:

- the study of scientific literature and normative documents that refer to the Industry 4.0 phenomenon;
- identifying the main factors that can stimulate the management of Romanian companies to accelerate the implementation of Industry 4.0 and ranking them according to their relevance for Romanian companies;
- identifying the main barriers that may inhibit the implementation of Industry 4.0 and ranking them according to their relevance for Romanian firms;

- establishing the maturity indicators that best characterize the firm under analysis and defining maturity levels and target levels;

- defining the actions needed to implement Industry 4.0 and identifying the limitations in the implementation process;

- defining a model for the implementation of Industry 4.0 and exemplifying its use by establishing the order of implementation of actions according to identified limitations and available resources;

- development of equipment to transform a classical machine into a cyber-physical system and establish algorithms for analyzing and reporting events;

- dissemination of the scientific and practical results of the research.

The thesis, which presents research aimed at achieving the proposed objectives, is structured in 5 chapters based on research presented in the literature. It continues with an analysis of the state of some Romanian companies regarding their maturity in terms of adopting systems and methods corresponding to the Industry 4.0 paradigm. The conclusions drawn allow to draw a path to be followed by the company in question, which will allow to go through the steps towards the implementation of Industry 4.0 concepts coherently, with minimum effort and maximized results. The conclusion presents the main conclusions drawn from the research and highlights personal contributions. A breakdown of the content of the thesis chapters is given below.

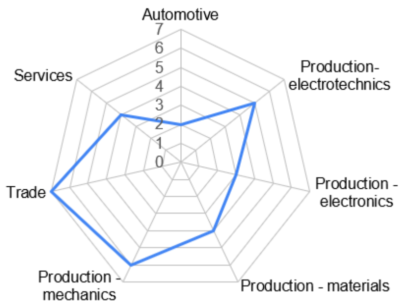
Chapter 1 – **The state-of-the-art of INDUSRTY 4.0 implementation** first presents historical aspects of industrial development and its stages, referred to in the literature as industrial revolutions [1]. It then looks at the fourth revolution, known as Industry 4.0 or Industrie 4.0, which is characterized by the exploitation of new technologies such as digitalization and the virtual world, sensor technology and the Internet [2-6]. These enable companies to integrate technical and business processes resulting in smart manufacturing.

The following presents national approaches and strategies related to the implementation of Industry 4.0, both for countries in Europe [7-12] and for countries in the Americas and Asia [13-15]. The changes brought about by this new revolution, now in full swing, are expected to have a positive effect on the efficiency and sustainability of industrial production [16], with direct implications for social relations and quality of life.

Fig. 1: Countries that have implemented national growth strategies

At the end of the chapter, the principles underlying the implementation of Industry 4.0 are presented and a classic adoption path is outlined.

Chapter 2 - **Analysis of the context in which the firm operates** investigates the environment in which the FIRM (name of the analyzed company is anonymized) operates and assesses its position within the partners. In this approach, 31 companies operating in various industries and of different sizes are analyzed. The analysis was carried out by applying a questionnaire containing three distinct parts. Figure 2 shows the structure of the companies responding to the questionnaire by sector of activity and the type of companies by turnover and number of employees.



Category	Micro	Small	Medium	Big
Turnover (Euro)	**6** ≤2 Mil.	**8** ≤10 Mil.	**8** ≤50 Mil.	**9** >50 Mil.
Average nr. of employes	**2** <10	**4** <50	**16** <250	**9** ≥250
Aggregated	**1**	**5**	**14**	**11**

Fig. 2: Structure of responding companies by sector of activity and type of company by turnover and number of employees

The study found that the level of knowledge about Industry 4.0 is limited, but many elements leading to the implementation of the new system are already being addressed by companies. The willingness of managers to collaborate in the sense proposed by the Industry 4.0 concept has been strongly expressed, which encourages FIRMA in its approach to implementing the new system. The decisive factors that make management think about implementing Industry 4.0 are efficiency and the market, as shown in Figure 3.

Fig. 3: Companies' perception of the weight of the ten factors stimulating the implementation of Industry 4.0

Grouping the results by domain gives the assessment shown in Figure 4. This allows easier comparison of the results of the present study with those in the literature [17-18], a comparison presented in Table 1. As a benchmark, works analyzing the situation in Eastern European countries, which have had similar social and economic development to Romania, were taken as a reference.

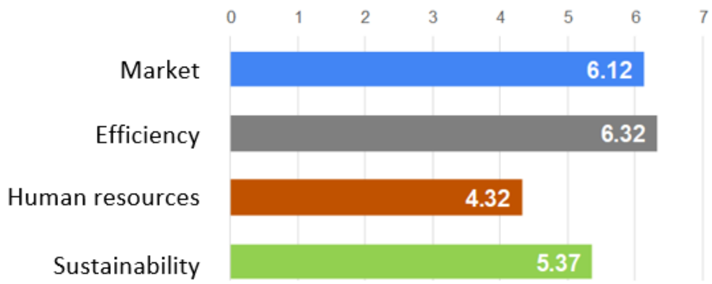


Fig. 4: Attention drawn to areas characterizing Industry 4.0 practices

Tab. 1: Effect of aggregated factors by domain on stimulating the implementation of Industry 4.0: comparison with foreign authors

Domain	Present study	Szabó et al.	Horváth and Szabó		Domain
	position	position	SMEs	Multinat.	
Efficiency	1	2	medium	medium	Productivity
		3	low	high	Profitability
Market	2	1	high	high	Customer satisfaction
		6	low	high	Market and competitors
Sustainability	3	4	low	high	Management
Human resources	4	5	high	low	Human resources

However, there are also concerns about implementation, and the study showed that the main concerns are related to the lack of human resources able to determine data transformation and security (Figure 5). On a positive note, the lack of financial resources is not a major fear for the vast majority of managers in the companies surveyed, indicating a willingness to collaborate in the context of Industry 4.0.

Fig. 5: Companies' perception of the weight of the ten factors that inhibit the implementation of Industry 4.0

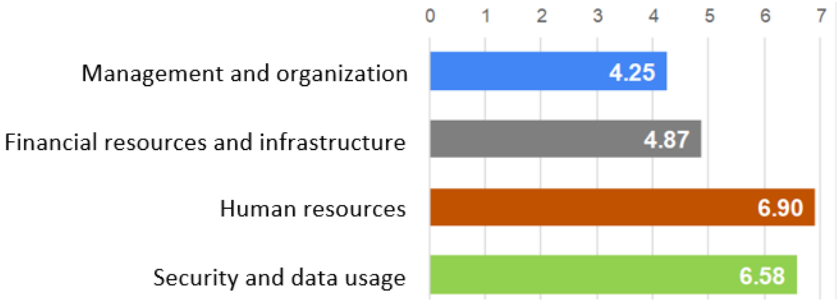


Fig. 6: Relevance of the domains that can slow down the implementation of Industry 4.0

The results of the analysis were compared, after grouping according to Figure 6, with those of studies presented in the literature [17-18], carried out in countries with a similar historical development to Romania, but also in other European countries. The approach of managers of Romanian firms is quite similar to that of managers abroad, with a similar ranking of the incentive barriers.

Tab. 2: Effect of factors aggregated by domain on slowing down the implementation of Industry 4.0: comparison with foreign authors

Domain	Present study	Szabó et al.	Horváth and Szabó		Domain
	position	position	SMEs	Multinaț.	
Human resources	1	1	high	medium	Human resources
Security and data usage	2	-	-	-	-
Financial resources and infrastructure	3	2	high	low	Financial resources
		3	low	high	Technology
Management and organization	4	4	high	medium	Management
		5	low	high	Organization

From the study, it was concluded that FIRMA and its partners under analysis accept the implementation of Industry 4.0, i.e. collaboration in this context of production organization. It is therefore appropriate to map out an implementation path, but this must take into account both the resources available to the FIRM and the areas in which the partners are prepared to cooperate.

Chapter 3 - **Establishing the company's path to Industry 4.0 implementation** builds on the results of the previous chapter. Having established that the firm's partners understand the digital transformation and are open to collaborating according to the new paradigm and that the firm has the openness to move to Industry 4.0 with all the financial implications, it is necessary to first establish the level of maturity at which the firm is currently. Following desk research but also discussions with managers and heads of various departments, the maturity levels at which the company currently falls were identified, by six domains divided into 35 sub-domains.

Considering the factors that stimulate the implementation of Industry 4.0 but also the barriers identified in the previous chapter, as well as the studies presented in the literature [19-21], we proposed six major areas for firm maturity analysis, namely:

1. Company products
2. Infrastructure
3. Organization
4. Supply and distribution chain
5. Business model
6. Data security and protection

Each of these areas has sub-domains or components, which are analyzed and evaluated separately. Each component will have four maturity levels associated with it, as follows:

Level I - Novice, where the component does not have the features required by Industry 4.0;

Level II - Intermediate, where Industry 4.0 features associated with the component under analysis are visible;

Level III - Advanced, which attests to an increased maturity in the direction of the component analyzed;

Level IV - Expert, awarded when all features associated with the component fully satisfy Industry 4.0 requirements.

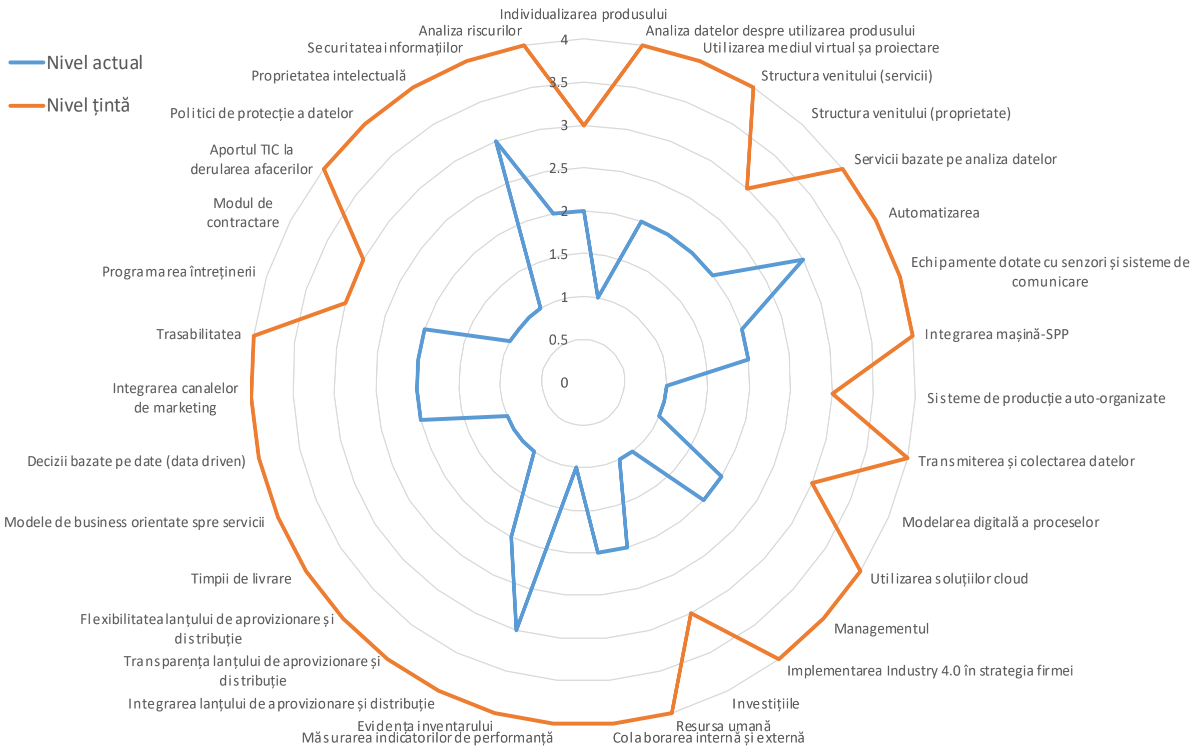


Fig. 7: Overview of the maturity of the firm – the blue line represents the current level and the orange line is the target level

Several specific factors, usually belonging to the nine pillars of Industry 4.0, contribute to achieving a certain level. These factors will be taken into account when determining the path to follow to implement the customized transformations at the company level.

Moving to a higher level of maturity involves meeting certain requirements, which implies specific actions. For all identified sub-domains, requirements have been inventoried and can be assimilated with expected results. One or more actions have been associated to each requirement. If the current level of maturity is high and the criterion is met from the outset, the required actions are no longer considered. The actions are then grouped according to their nature (training, procurement, development of procedures and strategies, etc.), and the chronological links between them and the level of costs required for implementation are established.

Four types of limitations were established for the implementation of the actions, consisting of limitations related to: the timing of the actions, the minimum duration of the actions, the financial resource requirements, and the human resource requirements. An example of the chronological sequence of actions is shown in Figures 8-11. Figure 8 represents actions related to *internal and external collaboration* as follows: purple represents actions related to internal and external collaboration only and green represents actions related to internal company analysis. Figure 9 shows the sequence of actions that relate to the functioning of *the Information System, decision-making, and data security*. Among the actions marked with blue, there is also an action marked with purple, which is specific to external collaboration but absolutely necessary to be able to ensure the partners' access to the firm's IT system. Figure 10 shows the sequence of actions aimed at *product development and promotion*. This objective contains the most actions, the first being more technically oriented and the latter concerning marketing and sales strategy. From the figure, it can be seen that here too actions related to internal and external collaboration interfere with those specific to the objective. The organization of production and maintenance actions, here named *Manufacturing*, requires a series of actions shown in Figure 11. These actions involve transforming machine tools into cyber-physical systems and integrating this equipment into the company's IT system. This objective has a smaller number of actions, but they are of high complexity and importance for the digital transformation of the firm.

Action	6.d.1				3	
Action	3.f.2			2		
Action	3.f.1		1			
Action	3.a.1-1	0				
Action	3.a.1-2		1			
Action	3.e.1			2		
Action	6.a.1				2	
Action	4.b.2					4
Action	1.b.1.					4

Fig. 8: Actions to address *Internal and external collaboration*

Action	2.c.1	0	1	2	3	4	5	6	7
Action	6.c.3	0							
Action	6.c.1		1						
Action	2.g.1			2					
Action	6.c.2				3				
Action	4.b.2					4			
Action	4.b.1						5		

Fig. 9: Actions targeting *IT, Decision-making, and Security*

Action	3.d.1-1	0							
Action	3.d.1-2		1						
Action	3.a.1-1	0							
Action	1.d.1		1						
Action	1.d.2			2					
Action	6.b.1				3				
Action	1.c.1					4			
Action	1.b.3						5		
Action	1.b.1.					4			
Action	1.b.2						5		
Action	1.a.1							6	
Action	1.d.3							6	
Action	5.c.1								7
Action	1.d.4								7

Fig. 10: Actions aimed at *Product development and promotion*

Action	3.d.1-1	0					
Action	3.d.1-2		1				
Action	2.a.1	0					
Action	1.a.2	0					
Action	2.b.1		1				
Action	2.a.2			2			
Action	2.f.1				3		
Action	4.b.2					4	
Action	1.e.1						5

Fig. 11: Actions to address the domain of *Manufacturing*

Using the information related to the actions required for the implementation of Industry 4.0, a model is developed that allows the actions to be phased in over time in a way that is sustainable in terms of the use of financial and human resources.

		month 1	month 2	month 3	month 4	month 5	month 6	month 7	month 8	...	month *M*		
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8	...	j=M		
action 1	i=1	c_{11}	c_{12}									c_1	cost action 1
action 2	i=2			c_{23}	c_{24}	c_{25}						c_2	cost action 2
action 3	i=3	c_{31}	c_{32}	c_{33}								c_3	cost action 3
action 4	i=4				c_{44}	c_{45}	c_{46}	c_{47}				c_4	cost action 4
action 5	i=5								c_{58}			c_5	cost action 5
action 6	i=6	c_{61}	c_{62}									c_6	cost action 6
action 7	i=7			c_{73}	c_{74}							c_7	cost action 7
...	...											...	...
action *N*	i=N											c_N	cost action *N*
		k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	...	k_M		
		expense	expense	expense	expense	expense	expense	expense	expense	...	expense		
		month 1	month 2	month 3	month 4	month 5	month 6	month 7	month 8	...	month *M*		

Fig. 12: Timetable matrix for the implementation of actions

For each action, an estimate of the cost is made, and the value is entered in the last column of the matrix (e.g. in the cost cell action 1 in Figure 12). The cost of each action is then divided into time periods during which the action is implemented, taking into account the mathematical relationship:

$$c_i = \sum_{j=1}^{M} c_{ij} \tag{1}$$

In the above relationship, the term represents the total cost of action *i,* and c_{ij} represents the cost of action *i* in month *j*. The values c_{ij} are entered in the program matrix in the colored cells for action *i*, and the sum c_i must correspond to the value of the cost of action *i* that was originally entered at the end of the row. Some activities can be fragmented and run before the need to use their results arises. This fragmentation postpones some expenses while ensuring the continuity of actions.

The total cost of implementing the actions, c_{total} , is determined as follows:

$$c_{total} = \sum_{i=1}^{N} c_i = \sum_{i=1}^{N}\sum_{j=1}^{M} c_{ij} \tag{2}$$

To ascertain whether financial resources are available at the time of programming actions and making payment obligations, the cost of implementation per month is calculated with the mathematical relationship:

$$k_j = \sum_{i=1}^{N} c_{ij} \tag{3}$$

where k_j is the expenditure incurred in month *j* and c_{ij} is the cost of action *i* in month *j*. The calculated values are passed to the penultimate row of the matrix and checked for compliance with the limits set for those months. If the expenditure limits are exceeded in certain months, there is the possibility of rearranging the actions by shifting or extending them over time. Depending on the way the company is financed, expenditure limits can also be set for longer periods of time, e.g. quarterly or half-yearly. In this case, it must be ensured that the sum of the expenditure for the months of the period concerned does not exceed the amount allocated to that period. The total expenditure incurred during the period of digital transformation is calculated with the mathematical relation:

$$k_{total} = \sum_{i=1}^{N} c_{ij} = \sum_{j=1}^{M}\sum_{i=1}^{N} c_{ij} \tag{4}$$

Since c_{total} has the same meaning as k_{total} the two values must be equal, so the program matrix provides a key to check the correctness of the calculation process and thus the staggering of actions over time. In the case of flexibility in the implementation period of actions, priority is given to those actions or series of actions which have an immediate effect. This immediate effect is not necessarily of a financial nature but ultimately leads to positive financial effects.

Unlike existing models, the proposed model looks at the transition holistically and has the advantage that it eliminates redundancies and the need to correct and adjust actions according to the transition history.

Chapter 4 - **A case study on the integration of a conventional machine tool into a self-organizing Industry 4.0 manufacturing line** presents an example of transforming production on a conventional manufacturing line into one that is controlled by IT-instrument systems, able to organize itself autonomously and determine the need for human intervention in case of abnormal operation or to ensure maintenance. This transformation is found to be necessary in the study presented in chapter three, in the area of infrastructure.

The manufacturing line used as a first example consists of three machines, shown in Figure 13, consisting of a cutting machine, a universal milling machine, and a machine on which components are assembled, one of which is produced on the milling machine. The research aims to implement an optical sensor and to develop the ALSO algorithm in a computer program that allows the machine to know its state and generate data that can be transmitted to various departments of the company (production, accounting, maintenance, etc.).

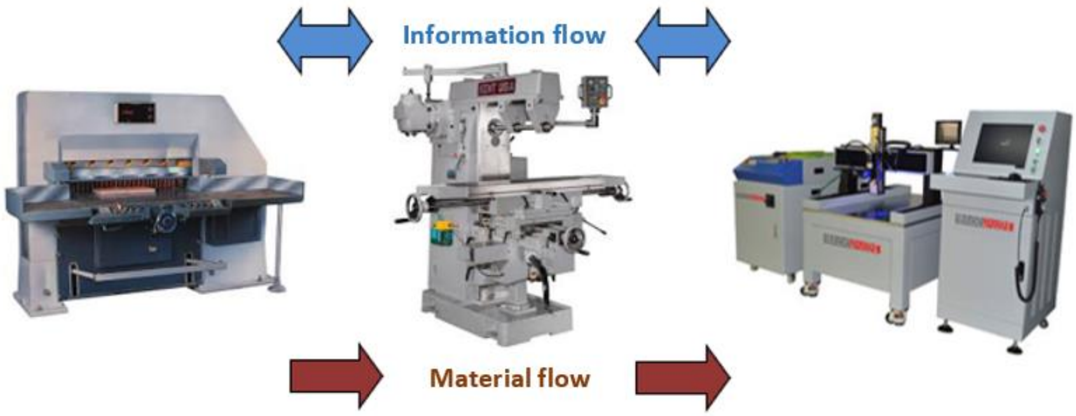


Fig. 13: Material and information flow diagram for the analyzed production line

Using the ALSO algorithm, reports can be generated periodically at set intervals on the number of products produced, the amount of scrap, and the uptime, maintenance, and downtime. Essentially, the algorithm is based on a signal given by an optical sensor focused on the workspace (workpiece). By analyzing the acquired signal, it is possible to determine the number of passes, the time required for a pass, the number of workpieces executed, the loading/unloading time, the machine's dwell time, etc. Real-time transmission of the information to a centralized system allows decisions to be made, even autonomously, regarding the operation of the other machines in the production flow.

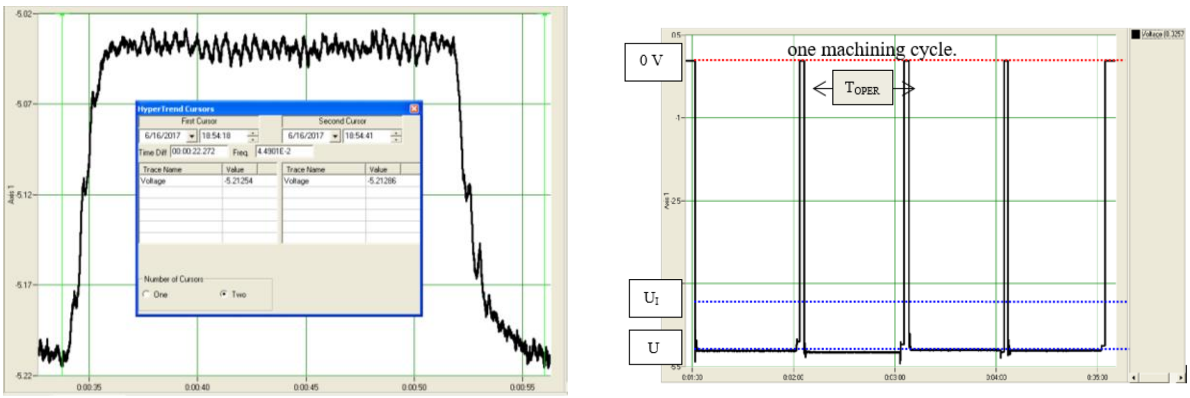


Fig. 14: Interface representing the displacement of the free end of the part for a pass, respectively for a complete cycle

A second example is the use of accelerometers placed on CNC machines and the development of an algorithm (ALMA) based on a classification and decision tree that has been designed to allow the identification and transmission of information related to machine status, production, and the time the machine is in use. The signal, acquired with an accelerometer, is analyzed in the time domain. Depending on the acceleration amplitudes, different machine and tool states, and production states can be distinguished. An example of a signal acquired during the manufacturing process and the amplitude limits for different machine states is shown in Figure 15.

The data obtained and processed in this way exceeds that normally obtained for even complex machines equipped with standard sensors, which only provide information on machine parameters (oil pressure, electricity consumption, etc.), and are also useful for departments not directly involved in production.

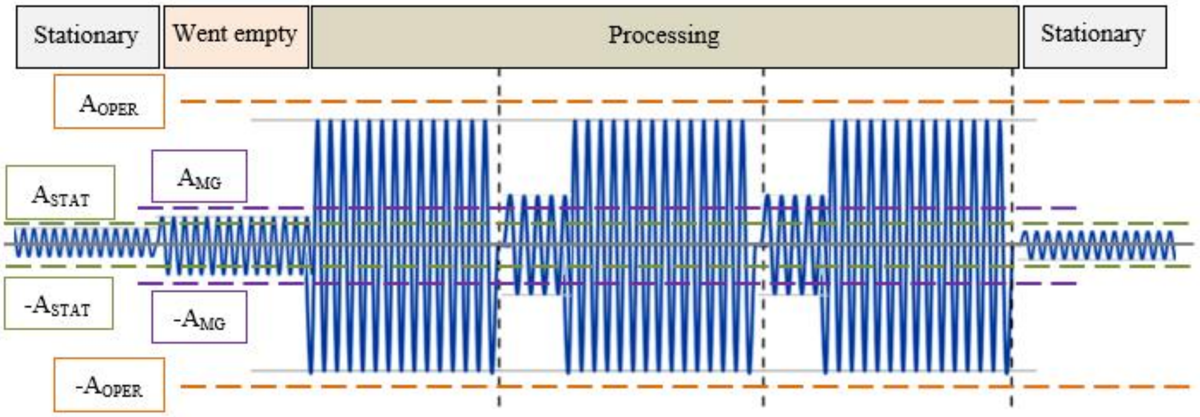


Fig. 15: Example of a signal acquired from the accelerometer during the process of manufacturing and amplitude limits for various machine states

The state of the machine and the operating mode are identified using the measured parameters entered in the classification and decision tree shown in Figure 16. The algorithm also allows highlighting the number of parts processed, and the number of rejects or parts for which not all processing operations have been performed.

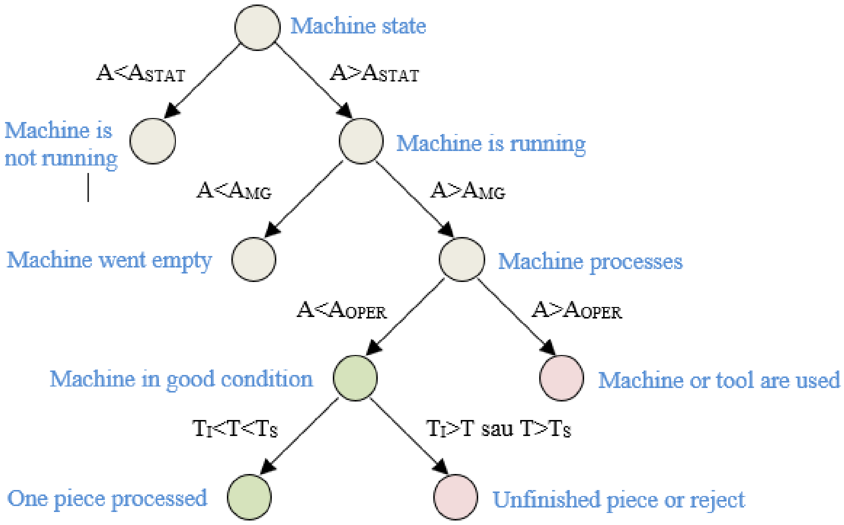


Fig. 16: The classification and decision tree underlying the ALMA algorithm

Information can also be transmitted to other machines in real time, and if the software is embedded in a global production organization program, the production flow becomes self-organizing. It has been found that it is simpler for algorithms to be developed individually, application-specifically, and then aggregated into a complex system whose structure can be designed a priori.

Chapter 5 - **Conclusions, personal contributions, and future directions for research development** reflect the results of the studies carried out, presenting the main conclusions drawn from the research and relevant original contributions. The following relevant contributions are highlighted:

- Defining and prioritizing according to relevance the main factors that can stimulate the management of Romanian companies to accelerate the implementation of Industry 4.0;
- Identify the main barriers that may hinder the implementation of Industry 4.0 and rank them according to the perception of Romanian companies' managers;
- Establishment of a system composed of 35 maturity indicators structured on six domains adapted to the analyzed company and definition of indicators characteristic of the four maturity levels;
- Setting target maturity levels by areas and indicators;
- Defining the actions needed to implement Industry 4.0 and identifying the limitations in the implementation process;
- Define an Industry 4.0 implementation model and exemplify its use by establishing the order of implementation of actions according to identified limitations and available resources;
- Definition of rules for prioritizing the actions carried out to establish the most rational route for implementing Industry 4.0
- Development of equipment that allows the transformation of a classical machine into a cyber-physical system and the establishment of algorithms for event analysis and reporting.

The results of the research have been published in peer-reviewed journals (3 articles in ISI-indexed journals and 3 in BDI-indexed journals) and conference volumes (1 ISI indexed, 2 Scopus indexed, and 1 BDI indexed). The list of papers with thesis elements is presented below.

1. Gillich EV, Nedelcu D, Popescu C, Self-management of machines in smart factories via advanced algorithms, Annals of the „Constantin Brancusi" University of Targu-Jiu. Engineering Series 1, 2019, pp. 65-69 (Index Copernicus)

2. Gillich EV, Mocan M, Mituletu IC, Korka ZI, Process Monitoring in Precision Machining using Optical Sensors, Romanian Journal of Acoustics and Vibration 14 (1), 2017, pp. 50-53 (ISI)

3. Haţiegan C, Gillich EV, Vasile O, Nedeloni MD, Pădureanu I, Finite Element Analysis of thin plates clamped on the rim of different geometric forms. Part I: Simulating the Vibration Mode Shapes and Natural Frequencies, Romanian Journal of Acoustics and Vibration 12(1), 2015, pp. 69-74 (ISI)

4. Haţiegan C, Gillich EV, Vasile O, Nedeloni MD, Jurcu M, Magheti P, Finite Element Analysis of thin plates clamped on the rim of different geometric forms. Part II: The Absolute and Relative Variation of Natural Frequencies, Romanian Journal of Acoustics and Vibration 12(1), 2015, pp. 81-86 (ISI)

5. Muntean F, Hatiegan C, Popescu C, Gillich EV, Iancu V, Study regarding the determining of the natural frequencies and modal shapes of the column type structures with additional mass, Annals of the „Constantin Brâncuși” University of Târgu-Jiu. Engineering Series 3, 2015, pp. 52-55 (Index Copenicus)

6. Nedelcu D, Gillich EV, Iancu V, Muntean F, Theoretical and Experimental Research Performed on the Tesla Turbine – Part II, Analele Universitatii "Eftimie Murgu". Fascicula de Inginerie 22(2), 2015, pp. 264-272 (Index Copernicus)

7. Gillich EV, Mocan M, Korka ZI, Gillich GR, Hamat CO, Real-time assessment of machine performance through the use of an intelligent sensorial system, The 10th International Symposium Machine and Industrial Design in Mechanical Engineering (KOD 2018) 6–8 June 2018, Novi Sad, Serbia, Publicat in IOP Conference Series: Materials Science and Engineering, Vol. 393, 2018, Art.ID 012082 (Scopus)

8. Mocan M, Gillich EV, Mituletu IC, Korka ZI, An evolutionary sensor approach for self-organizing production chains, International Conference on Applied Sciences (ICAS2017) 10–12 May 2017, Hunedoara, Romania, Publicat in IOP Conference Series: Materials Science and Engineering, Vol. 294, 2017, Art.ID 012092 (Scopus)

9. Gillich EV, Mocan M, Cei nouă piloni ai noii revoluții industriale – INDUSTRY 4.0, publicat in Știința si Inginerie 31, 2017

10. Negru I, Gillich GR, Praisach ZI, Tufoi M, Gillich EV, Nondestructive evaluation of piers, Health Monitoring of Structural and Biological Systems 2015, Art.ID 943817 (ISI).

The research conducted during the doctoral studies led to the development of an Industry 4.0 transition model applicable to a medium-sized firm operating in the field of electrical equipment manufacturing. The data available were relevant and the duration of the study sufficiently focused to generate an overview of the firm and its environment.

One direction for further research is to establish the viability of the methodology and to make corrections or calibrations after monitoring the implementation in the context of current technological changes and the running of processes in a dynamic economic environment.

The studies carried out also open up a research direction related to finding data analysis algorithms, possibly with the inclusion of artificial intelligence elements, to enable automated decision-making for more complex production structures.

The thesis concludes with a list of bibliographical references and appendices, which present the national programs related to Industry 4.0 in the European Union countries, the list of companies and the questionnaire applied to them, and the current maturity levels versus those proposed to be reached by the FIRM.

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