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INTEGRATED LEAN MANUFACTURING AND ITS APPLICATION AT WORKSTATION LEVEL

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Abstract: *Lean Manufacturing (LM) means a production method aimed at wastes minimizing in manufacturing. Despite the issue being of high interest, the lack of concrete techniques for its application in practice can be noticed. The opportunities brought by Industry 4.0 concept are enabling a new approach to the LM concept. This paper aims to develop a methodology for its application, grounded on integrating the concept in manufacturing procedure. This can be obtained by addressing the LM desiderata as performance indicators to be included in the manufacturing task definition together with descriptor-variables. According to the proposed methodology, LM could be specifically applied to each level of manufacturing management. The manufacturing station level is here approached, with focus on scheduling & programming actions.*

Key words: *Lean Manufacturing, Integrated manufacturing, Performance modeling, Operation management, Decision-making methodology.*

1. BACKGROUND

Manufacturing is a particular form of production and refers to the processing of raw materials or parts into finished goods through the use of tools, human labor, machinery, and chemical processing [1].

The manufacturing management plays a crucial role in enabling the required competitiveness on market while its main target is the manufacturing performance. It refers to those aspects of the product manufacturing process that impact the value addition [2].

Operation management is concerned with converting materials and labor into goods and services as efficiently as possible to maximize the profit of an organization [3]. At this level, the performance indicators can be defined as physical values which are used to measure, compare, and manage the overall organizational performance [4]. At higher levels, the Enterprise Resources Planning (ERP) platforms operate with so-called Key Performance Indicators (KPI-s), among which top 5 are: Production Volume, Production Costs, On-time Delivery, First Time Right, and Revenue per Employee [5].

Operations management is one of the critical areas where the use of Industry 4.0 technologies gives benefits like increased flexibility, cost reduction, better service, higher product customization, and many more [6]. More concepts, among which Lean Manufacturing, have been developed in recent years in order to enable the enhancement of operations management efficiency.

Lean production and Industry 4.0 are two concepts regarding both management and manufacturing. They have been studied during recent years, also by focusing on the relationship that exist between them [7]. Several authors even state that Lean Manufacturing cannot be efficient without the implementation of Industry 4.0 technologies [8-10].

The following section presents a synthesis of the main issues from the current approach regarding Lean Manufacturing and states the challenge to be faced in this paper. The third section introduces the Integrated Lean Manufacturing concept, while the fourth section proposes a methodology for implementing it. The fifth section deals with an illustrative exercise, while the last is for conclusion.

2. APPROACH OF THE LEAN MANUFACTURING CONCEPT

After analyzing the literature dedicated to Lean Manufacturing concept, some definitory issues regarding the conventional approach of the subject can be highlighted as below presented.

- In relation to manufacturing issue, "lean" is an adjectival attribute of the manufacturing, which defines that manufacturing process that generates less waste [11].
- Waste meaning is that part of the material consumed that: *i)* Does not generate added value, and *ii)* Can be avoided. In other words, waste means unwanted or unusable material, substances, or by-products, where by-product means something produced in a usually industrial or biological process in addition to the main product.
- In relation to Lean Manufacturing, the waste meaning is expanded, in the sense that it refers to all the manufacturing resources consumed. Thus, seven types of potential waste have been identified in a manufacturing process, namely: *Overproduction*, *Needless inventory*, *Defects*, *Non-value Processing*, *Excess motion*, *Transport and handling*, and *Waiting* [12].
- Lean Manufacturing refers to the desirability of minimizing the amount of waste resulting from the manufacturing process, regardless of their nature.
- Lean manufacturing is about ways to reduce waste. Thus, 35 such tools were found, including *Just-in-Time*, *Kanban*, *Kaizen*, *Jidoka*, *Value Stream Mapping*, and others [13]. Each of them refers to the satisfying of a certain desire.

The challenge for this paper is related to the fact that both Lean Manufacturing tools and types of waste are interdependent, they are contradictory, they refer to different areas that overlap more or less, and they cannot all be used or minimized at once. Although the semantics of the concept are clearly grounded, the implementation of Lean Manufacturing is still based on *disparate conjunctural observations*. For this reason, *the development of a methodology to implement Lean Manufacturing* represents a significant challenge.

3. THE CONCEPT OF INTEGRATED LEAN MANUFACTURING

This paper answer to the challenge from above is the substantiation of a new type of manufacturing, namely the *Integrated Lean Manufacturing*, together to the *development of a methodology for its implementing*.

The concept is distinct to the existing approaches due to the following definitory issues: *i)* The manufacturing process is considered as *decisional process*, and *ii)* The *lean* attribute of the manufacturing process is approached in *integrated manner*.

3.1 Decisional Approach of the Manufacturing Process

The proposed approach is characterized by some specific issues, presented below.

- By *task* it is meant the changing of product state from current one up to the final one.
- The *manufacturing process* is comprised as the accomplishment of a given task and consists in more *decisional sequences*.
- Each decisional sequence consists of three actions: the decision-making action, the decision-execution action, and the decision-learning action (Fig. 1).

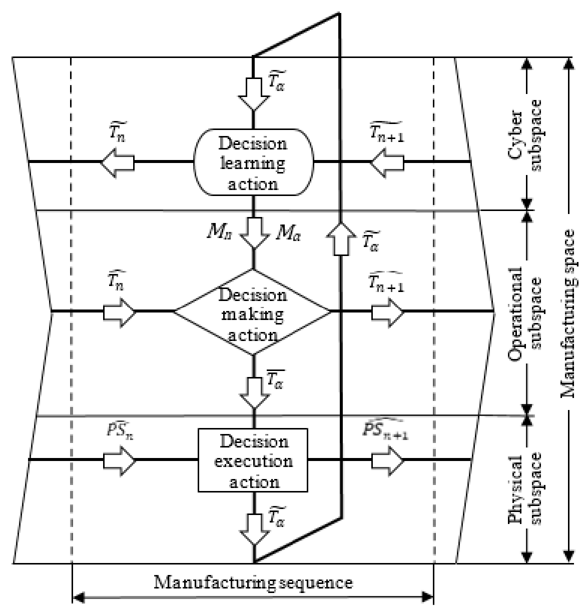

Fig. 1. Diagram of the decisional sequence

The *decision-learning action* consists in the conversion of information coming from monitoring into knowledge.

The *decision-making action* consists of making the following types of decisions:

- *Modeling decisions*, related to the configuring of the model M_n,
- *Planning decision*, which concerns the configuring of the input task, T_n into multiple output tasks, which may be executive tasks, T_α, and/or released tasks, T_{n+1}, and
- *Programming decisions*, related to the configuring of executive tasks T_α into programmed tasks, T_α.

The *decision-execution action* means the conversion of the programmed task, T_α, into the accomplished task, T_α.

The task is described by:

- Features,

$$\boldsymbol{T_{features}} = \{\boldsymbol{S}, \boldsymbol{P}, \boldsymbol{Q}\}, \quad (1)$$

where the vector $\boldsymbol{S}$ is regarding product state change, $\boldsymbol{P}$ – process performing, and $\boldsymbol{Q}$ – operating condition are the task features and represent the task *definitory* elements,

- Attributes,

$$\boldsymbol{T_{attributes}} = \{\boldsymbol{S_A}, \boldsymbol{P_A}, \boldsymbol{Q_A}\}, \quad (2)$$

which describe the features (1) and represent the task *descriptive* elements, and

- Variables,

$$\boldsymbol{T_{variables}} = \{\boldsymbol{v_1}, \boldsymbol{v_2}, \dots\ \boldsymbol{v_i}, \dots\ \boldsymbol{v_n}\}, \quad (3)$$

which describe the manufacturing process and represent the task *quantitative* elements.

Some remarks concerning the task description must be done.

a) The meaning of variables (3) depends on the way of approaching the process, as follows.

In *conventional* approach, they describe the physical process, and they may be classified as:

- Product-variables, $\{\boldsymbol{s_i}\}$,
- Performance-variables, $\{\boldsymbol{p_j}\}$, and
- Process-variables, $\{\boldsymbol{q_k}\}$.

In *decisional* approach, they describe the decisional process, and they may be classified as:

- Hypothesis-variables, $\widehat{\boldsymbol{T}}$,
- Decision-variables, $\overline{\boldsymbol{T}}$, and
- Result-variables, $\widetilde{\boldsymbol{T}}$.

b) A variable $\boldsymbol{v_i}$ is represented by its attribute, criterion, metric of evaluation, and value. Here value means the level of the criterion according to its metric. In other words, for such a variable, not only the value, but also the significance varies.

c) Some of the variables can be vectors, that is, they have several components that value the variable, similar to the case of the variable defined as the position-vector of a point. The difference between two values of this vector variable is also a position-vector, whose components are the differences between the components of the two vectors. In other words, even if the value of a variable is encoded, there is a metric of that variable, but a vector-metric.

d) The value of a variable describes one of the available options. For example, in the case of tool-variable, the values might be Tool no. 3 or Tool no. 4, which are two options. Although the values of this variable are coded (3 or 4), they are still comparable, that is, there is a metric of the tool-variable. Thus, the difference between the two values of the tool-variable is the difference between the vectors that describe the consequences of using one or the other of them. In other words, here the metric is vector.

e) A family of tasks having the same hypothesis variables, $\widehat{\boldsymbol{T}}$ represent a *job* is. These tasks are differentiated from each other by the values of the variables $\widehat{\boldsymbol{T}}$, or by definitions and values of the rest of the variables.

The job is described by the definitions of hypothesis variables and refers to the options available to achieve a specific, generic change in the state of the product, i.e., to perform a generic task.

3.2 Integrated Approach of Lean Manufacturing

"Lean manufacturing" is conventionally approached as the attribute of manufacturing that refers to the extent to which the desirability of *minimization of resource waste* is achieved, *regardless of resource nature*.

The integrated approach of Lean manufacturing introduced here is based on the remarks from below.

- When manufacturing is approached as a decision process, the information flow is:
- The attributes can be classified as *requirement*-attributes - $\{\boldsymbol{S_A}\}$, *option*-attributes - $\{\boldsymbol{Q_A}\}$, and *decision*-attributes - $\{\boldsymbol{P_A}\}$.

Related to the decision cycle, the attributes $\{S_A\}$ and $\{Q_A\}$ represent the *hypothesis*, while the attributes $\{P_A\}$ - the *decision*.

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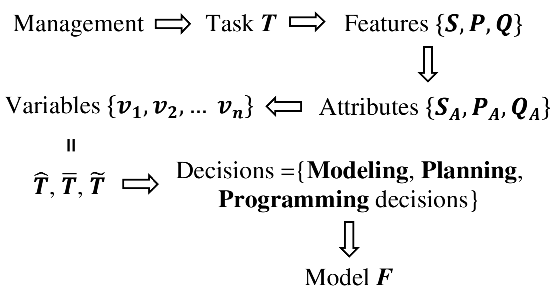

- The attributes (2) can be of either *quantitative* or *qualitative* type. The variables of the quantitative type have *fixed values*, while the values of the qualitative type tend to a *fixed reference*.
- The *qualitative* requirement-attributes, such as *parsimonious, cheap, efficient, productive, energy-efficient, flexible, precise, simple*, refer to $\boldsymbol{S}$ feature, show the performance waste requirements, and are described by variables $\widehat{\boldsymbol{T}}'$ (see Table 1)**.** Some explanations will be further delivered on the base of the following example. The attributes "cheap = minimum cost", "productive = minimum time", and "energy-efficient = minimum consume of energy" mean zero wastes of performance. If they concomitantly happen, then the total performance waste is zero. However, this is not actually possible in practice. In general, at most one can be zero, at a given time, while the others take higher values. Hereby, performance losses do exist in their cases. In other words, it must be accepted that the total performance waste can never be zero, so it will always be a performance waste. The *qualitative* requirement-attributes show the requirements regarding the performance wastes.
- The *qualitative* option-attributes, such as *LM* (Lean Manufacturing), *CIP* (Continuous Improvement Process), *JIT* (Just In Time manufacturing), *MTO* (Make To Order), *AM* (Agile Manufacturing), *VSM* (Value Stream Mapping), *6S* (Six Sigma), *KB* (Kanban), etc. refer to $\boldsymbol{Q}$ feature, show the options to minimize the performance waste, and are described by $\widehat{\boldsymbol{T}}''$ variables (also see Table 1).
- The *qualitative* requirement- and option-attributes are causally linked (see Table 2).

The Tables 1 and 2 are supposed to be used together to meet the requirement-attributes by appropriately selecting option-attributes, as it will be further seen.

- The *qualitative* decision-attribute is *Integrated-Lean* and is described by variables $\{\overline{\boldsymbol{T}}, \widetilde{\boldsymbol{T}}\}$.

Table 1

Integrated Lean manufacturing attributes.

PRODUCT STATE feature - *S* **Quantitative and qualitative requirement-attributes –** $\{S_A\}$ **Hypothesis variables -** $\widehat{\boldsymbol{T}}'$							
Qualitative requirement-attributes							
Parsimonious	Cheap	Effective	Productive	Low-energy	Flexible	Precise	Simple

PROCESS PERFORMING feature - *P* **Quantitative and qualitative decision-attributes –** $\{P_A\}$ **Decision variables -** $\{\overline{\boldsymbol{T}}, \widetilde{\boldsymbol{T}}\}$
Qualitative decision-attribute
Integrated-Lean - minimal performance waste

OPERATING OPTIONS feature – *Q* **Quantitative and qualitative option-attributes -** $\{Q_A\}$ **Hypothesis variables -** $\widehat{\boldsymbol{T}}''$											
Qualitative option-attributes											
LM	CIP	JIT	MTO	MTS	AM	VSM	SSM	KB	FM	CM	QC

Table 2

Causal relationships between the qualitative option- and requirement-attributes

Option \ Requirement	Parsimonious	Cheap	Effective	Productive	Low-energy	Flexible	Precise	Simple
Lean manufacturing (LM)	x	x	x					
Continuous improvement process (CIP)		x	x	x	x	x		
Just in time (JIT)	x	x	x					
Make to order (MTO)	x		x			x		
Make to stock (MTS)	x			x			x	x
Agile manufacturing (AM)				x	x	x		
Value stream mapping (VSM)	x		x	x				
Six Sigma (6S)		x	x	x			x	
Kanban (KB)	x		x					
Flexible manufacturing (FM)	x			x	x	x		
Cellular manufacturing (CM)	x			x	x			x
Quick changeover (QC)				x				x

4. INTEGRATED LEAN MANUFACTURING METHODOLOGY

The methodology is applied at the level of a given job by three successive actions: *i)* Job description, *ii)* Job modeling, and *iii)* Performance- & model-based control of process.

4.1 Job Description

A job is characterized through specific *features* and the qualitative and quantitative *attributes* that describe them.

Job describing means *to establish* the variables $\{v_1, v_2, \dots\ v_i, \dots\ v_n\}$ that define the *given job attributes* $\{\boldsymbol{S_A}, \boldsymbol{P_A}, \boldsymbol{Q_A}\}$, followed by *assigning each variable* to one of the three groups of variables $\{\widehat{\boldsymbol{T}}, \overline{\boldsymbol{T}}, \widetilde{\boldsymbol{T}}\}$.

The variables of the *quantitative attributes* are established by concretely describing the manufactured product and the available assets.

Regarding the variables of the *qualitative attributes*, they are established in such a way as to describe the *performance* (this reflecting the managerial tactic adopted). Here, the qualitative *requirement-attributes* provide the *performance requirements*, while the qualitative *option-attributes* provide the *available options* to satisfy these requirements.

The variables of the *qualitative attributes* are established by: *i)* Pairing qualitative requirement -attributes with qualitative option-attributes, according to the causal relationships between them (Table 2), so that the managerial tactic is adequately described, *ii)* Selecting the variables that describe these pairs and *iii)* Establishing the variables that describe the performance as the ones of $\{v_1, v_2, \dots\ v_i, \dots\ v_n\}$ whose values are the measure of how close the values of the other variables are to a given reference. Let v_1 and v_n be the variables giving the predicted, respective the measured values of performance.

A *reference* and a *metric* are necessary to describe the performance. By *reference* it is meant a set of values $\{r_2, r_3, \dots\ r_{n-1}\}$ of the variables $\{v_2, v_3, \dots\ v_{n-1}\}$, further called reference values**.** The *metric* is a *function H***,** through which the performance is defined by report to the reference values $\{r_2, r_3, \dots\ r_{n-1}\}$ and to the other variables of the task $\{v_2, v_3, \dots\ v_{n-1}\}$.

4.2 Job Modeling

This action means to build the digital model of causal relationships between the variables, as $F(v_1, v_2, \dots\ v_i, \dots\ v_n)$. The job model may take one of the following forms:

- Elementary model, *f*, formalized as a set of values for $\{\widehat{\boldsymbol{T}}, \overline{\boldsymbol{T}}, \widetilde{\boldsymbol{T}}\}$ variables,
- Implicit model, *F*, formalized as a set of N elementary models, *f*, and
- Explicit model, F_m, formalized as the m-set of elementary models, *f*, for which some of the variables are nominated as effect-variables, while the other are considered to be condition-variables.

The job model is obtained by composing models, be they elementary, implicit, or explicit. The elementary models result by applying the holistic monitoring of process performing [14].

The algorithm of job model building is illustrated in Fig. 2 and comprises three steps.

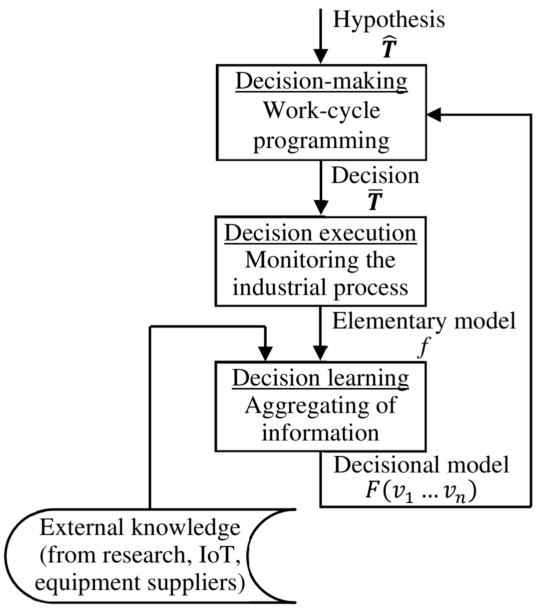

Fig. 2. The building of job model

The input consists in the values for $\widehat{\boldsymbol{T}}$ hypothesis-variables. At the first step, decisions regarding the required manufacturing process are made, the values for $\overline{\boldsymbol{T}}$ decision-variables being thus obtained. Next step concerns the process monitoring, finalized by finding out the values of $\widetilde{\boldsymbol{T}}$ result-variables, so the elementary model f corresponding to current process iteration is also found. At last step, this model is aggregated with already existing similar models (from external knowledge) and an updated form of Fdecisional model finally results.

4.3 Performance and Model-Based Control of the Process

The proposed control of manufacturing concerns the actual value of process performance waste, as controlled variable, while the control variable is the process model.

The resulted performance is online monitored and evaluated on the base of $\widetilde{\boldsymbol{T}_{\alpha}}$ vector (see Fig. 1), which is communicated by feedback loop from *Decision execution* action to *Decision learning* action. If differences are noticed between the required and the obtained levels of performance, then both models (M_n and M_α) are consequently adjusted to enable the reaching of targeted performance.

4.4 Novelty, Benefits & Limitations

- The core novelty of the paper is that *Integrated-Lean Manufacturing* means the *rational process of transforming resources into products* characterized by *performance waste minimization*, instead of resource waste minimization, as *LM* currently is.
- The main benefit is that all tools available for performance increase are capitalized.

Moreover, the *performance* is defined as an *appropriate function* of the process variables, while the shape of the performance function reflects the *managerial tactics*.

- The main limitation is the need to monitor all process variables and to invest in an IT system to support an extensive information flow among decision makers.

5. ILLUSTRATIVE EXERCISE – INMPLEMENTATION OF INTEGRATED LEAN MANUFACTURING AT WORKSTATION LEVEL

An illustrative exercise of Integrated Lean Manufacturing implementation is further presented, for a better understanding.

Let us consider the implementation of Integrated Lean manufacturing at the level of a workstation for a turning job. The features, attributes and variables selected for describing the addressed job are presented in Table 3.

Regarding the reference used to describe the performance, in the addressed exercise, it will be adopted as the set of extreme values for the cost, metal removal rate and consumed energy:

$$\{r_7, r_8, r_9\} = \{C_{min}, MRR_{max}, E_{min}\}. \quad (4)$$

The performance metric will be defined as:

$$v_1 = Max(|v_7 - r_7|, |v_8 - r_8|, |v_9 - r_9|). \quad (5)$$

In Table 4 is presented a sample set of elementary models, corresponding to the turning of eight different parts, extracted from a larger instances database, artificially built [15].

Table 3

Features, attributes and variables of the turning job

Features					
S – Product requirements		P – Process performing		Q – Operating options	
Attributes					
Quantitative	Qualitative	Quantitative	Qualitative	Quantitative	Qualitative
Part geometry accuracy, roughness, and material	Cheap, Productive, & Energy-efficient	Set conditions of process performing	***ILM*** Integrated Lean Manufacturing	Power, Cutting regimes, Tools capacity.	***CIP*** and ***JIT***
Variables					
Part required: v_2 – length [mm], v_3 – diameter [mm] v_4 – accuracy level v_5 – material strength, v_6 – stiffness level.	Requirements: v_{13} – cost [Euro], v_{14} – metal removal rate [cm^3/min], v_{15} – consumed energy, [KWh].	Set values of: v_{16} – cutting speed, [m/min], v_{17} – feed, [mm/rev], v_{18} – cutting depth, [mm].	Predicted value of: v_1 – performance waste [%], v_7 –cost [Euro], v_8 – metal removal rate, [cm^3/min], v_9 – consumed energy, [KWh].	Limited value of: v_{10} – cutting force, [N], and v_{11} – installed power, [KW].	v_{12} – time window [min], and v_{19} – resulted performance waste, [%].
Hypothesis-variables – $\widehat{\boldsymbol{T}} = \{v_2 \dots v_6, v_{10} \dots v_{15}\}$, Decision-variable – $\overline{\boldsymbol{T}} = \{v_1, v_7 \dots v_9, v_{16} \dots v_{18}\}$, and Result-variables – $\widetilde{\boldsymbol{T}} = \{v_{19}\}$.					

Table 4

Turning job model

V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**	**V11**	**V12**	**V13**	**V14**	**V15**	**V16**	**V17**	**V18**	**V19**
87.4	200	69	1.4	7.3	3.5	7.71	10.12	0.79	170	2.55	4.5	6.1	41.2	0.79	45.5	0.38	1.8	87.6
61.2	169	93	6.3	2.1	7.2	6.1	29.2	1.64	162.4	4.4	3.3	6.1	41.2	0.79	134.7	0.18	3.6	60.8
49.4	284	150	2.7	3.4	8.4	13.8	41.2	1.39	317.8	5.1	6	6.1	41.2	0.79	90.4	0.33	4.2	49.1
69.7	126	102	8	3.6	7.4	9.12	16.4	0.92	123.7	3.5	4.1	6.1	41.2	0.79	114.3	0.12	3.7	70.2
34.2	270	150	6.4	1.1	4.6	10.1	29	1.02	98.4	4.3	4.6	6.1	41.2	0.79	214.1	0.18	2.3	34.3
58.4	300	148	5.7	2	8.5	15.2	39.3	1.53	211.3	5	6.4	6.1	41.2	0.79	136.1	0.21	4.3	57.6
100	280	143	2.7	8.4	5.7	21.7	16.8	2.17	253	3.4	8.9	6.1	41.2	0.79	54.1	0.13	2.9	100
100	156	124	6.6	7.5	3.5	18.8	5.6	1.88	88.8	2.05	7.8	6.1	41.2	0.79	57.1	0.17	1.7	100

The *ILM* methodology was implemented as above-explained, on the base of these numbers, as hypothesis. The curves depicted in Fig. 3 represent the wastes of cost, energy, metal removal rate, and performance – the last one defined according to (5).

By analyzing the results, one can notice that, as already noticed in paragraph 3.2, the wastes of cost, energy and MRR cannot be simultaneously zero. Moreover, they have a wide variation range, comprised between 0 and 100 % for each. As consequence, two things must be noticed:

- The performance waste is never zero – the minimum value is 34.3%, in the case of the fifth part, and

- The application of *LM* traditional concept, by taking into account only one of the three types of waste could lead to a significantly high level of general performance waste. For example, when consumed energy waste is zero, *MRR* waste, hence performance waste too, are about of 90 %.

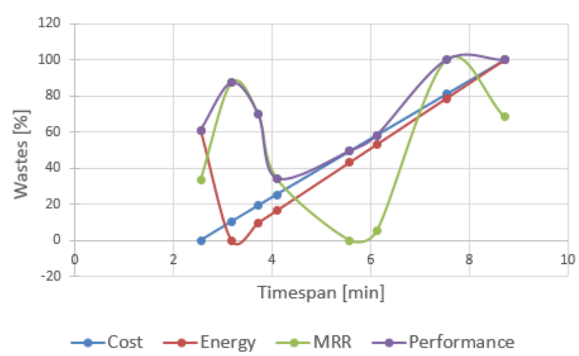

Fig. 3. Evaluation of wastes

6. CONCLUSION

Integrated Lean Manufacturing, proposed here, is a waste management technique motivated by performance outcomes, tailored to use cases, powered by integration, and built on current data. It is motivated by performance outcomes because it refers to the control of performance waste defined according to a particular management policy. It is tailored to use cases because the model this technique is based on is job specific. It is powered by integration, because all wastes and all waste reduction options are taken into account when the decision is made. It is built on actual data because the control model is built online, based on data from monitoring.

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Fabricaţia de tip „lean" integrat şi aplicarea sa la nivelul staţiei de lucru

Fabricația „lean" (LM) este o metodă de producție ce urmărește minimizarea pierderilor. Deși subiectul prezintă mare interes, se poate remarca o lipsă a tehnicilor necesare pentru aplicarea concretă în practică. Oportunitățile create de dezvoltarea conceptului „Industry 4.0" oferă o nouă abordare conceptuală a LM. Lucrarea de față își propune dezvoltarea unei metodologii de aplicare bazată pe integrarea conceptului în procedura de fabricaţie. Aceasta se poate realiza prin considerarea dezideratelor LM ca indicatori de performanţă urmând a fi incluşi în definiţia sarcinii de fabricaţie, alături de variabilele descriptoare. Potrivit metodologiei propuse, LM poate fi aplicat în mod specific la fiecare nivel de management al fabricaţiei, aici fiind abordat nivelul staţiei de lucru, cu focalizare pe acţiunile de ordonare şi programare.

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