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Technical Paper

Lean rules extraction methodology for lean PSS design via key performance indicators monitoring

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ABSTRACT

Lean PSS (Product-Service System) design comprises a promising strategy for delivering sustainable PSS offerings, considering several well-established lean practices. However, automated ways to apply lean practices and more specifically lean rules in industry are limited. This work proposes a methodology for improving the leanness of PSS design, by combining real-time KPI monitoring with lean principles and practices. Through a correlation of typical wastes with the metrics used in the calculation of KPIs, the Total Leanness Index (TLI) of the procedures is defined. Based on automatically identified trade-off values for TLI, lean rules are extracted to improve the performance of PSS lifecycle phases. The proposed lean rules extraction methodology (LeanREM) is validated through a case study of power waste reduction and the concurrently maintenance time decrease in a mould-making company.

1. Introduction

For several decades, cost and production rates have been the most important performance indicators, while industry focused solely on the product as a means of value creation. The transition from local economies to the global competitive landscape, the current fluctuating customer demands, socio-political reasons, and the technological advances, led to the evolution of manufacturing systems from craftsmanship to customer-oriented manufacturing paradigms [1]. Thus, indicators related to customer, sustainability, and leanness have been embedded in manufacturing systems in order to meet the need for an environmentally conscious mass customisation paradigm [2], where value is encapsulated in the hybrid solution of Product-Service Systems (PSS) [3]. Practice nowadays focuses on strategies and methods for managing product, process, and production systems development that are capable of supporting product variety, adaptability, and leanness, built upon the paradigms of mass customization and product personalization [4]. Novel concepts for the servitisation of manufacturing are being adopted and a shift towards the Industrial Product Service System (IPSS) paradigm and leanness is observed, in order to sustain competitiveness [5]. Research carried out between 2007 and 11, shows that 30% of worldwide manufacturers shifted their business strategy to offer services [6]. Despite the importance and the adoption rate of PSS form of value proposition in the industry, research fields established by the constituents of PSS are still inadequately covered [7–9]. More specifically, methodologies and frameworks for assessing the performance of PSS to reach a higher level of leanness are still immature [10,11]. Contributing to the filling of these gaps, this paper proposes an automated of lean rules extraction methodology (LeanREM) via real time monitoring of Key Performance Indicators (KPIs), aiming to dynamic, adaptable, robust, and reconfigurable lean PSS designs.

In Section 2, a review of relevant state of the art on PSS and Lean concept is provided. Section 3 describes the LeanREM via KPIs. Section 4 presents an ontology model for lean rules extraction. Section 5 presents a case study from a mould-making SME. Finally, Section 6 concludes the paper.

2. State of the art

Since the resources and energy are finite, new sustainable ways of producing more with less, while focusing on eco-innovative technologies, as the PSS concept promises, ought to be established [12]. In line with this eco-friendly view, PSS has a clear heritage in lean

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Abbreviations: PSS, product service system; KPI, key performance indicator; IPSS, industrial product service system; CM, context model; LR, lean rules; TLI, total leanness index; LI, leanness index; W, waste type; WSN, wireless sensor network; RPM, revolutions per minute; TPM, total productive maintenance; JIT, just-in-time; AHP, analytic hierarchy process; TW, typical waste; P, parameter; M, metric; Ph, PSS lifecycle; LP, lean practice; EC, energy consumption; MT, maintenance time; MC, maintenance cost; MRT, maintenance reporting time; SMED, single minute exchange of dies; OEE, overall equipment effectiveness; PDCA, Plan, Do, Check, Act; SBL, Six Big Losses.

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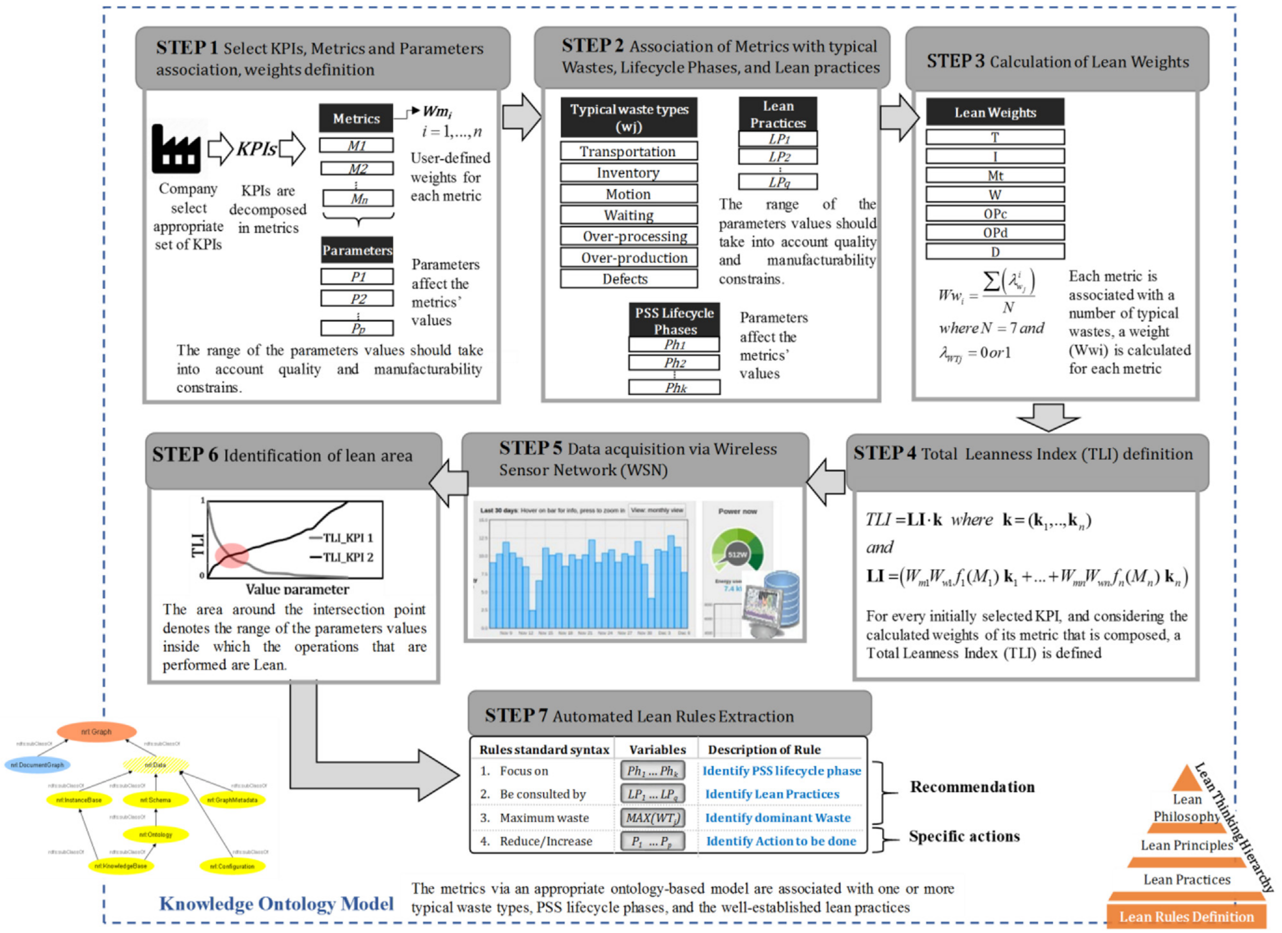

Company select appropriate set of KPIs

KPIs are decomposed in metrics

User-defined weights for each metric

Parameters affect the metrics' values

The range of the parameters values should take into account quality and manufacturability constrains.

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Parameters affect the metrics' values

Each metric is associated with a number of typical wastes, a weight (Wwi) is calculated for each metric

For every initially selected KPI, and considering the calculated weights of its metric that is composed, a Total Leanness Index (TLI) is defined

The area around the intersection point denotes the range of the parameters values inside which the operations that are performed are Lean.

Rules standard syntax	Variables	Description of Rule
1. Focus on	$Ph_1 \ldots Ph_k$	Identify PSS lifecycle phase
2. Be consulted by	$LP_1 \ldots LP_q$	Identify Lean Practices
3. Maximum waste	$MAX(WT_j)$	Identify dominant Waste
4. Reduce/Increase	$P_1 \ldots P_p$	Identify Action to be done

The metrics via an appropriate ontology-based model are associated with one or more typical waste types, PSS lifecycle phases, and the well-established lean practices

Fig. 1. Lean Rules Extraction Methodology (LeanREM) based on real time monitoring KPIs.

manufacturing, as defined in [13], and in Lean Product Development methodology. Over the years, Lean Thinking has been defined and coded as a dynamic, knowledge-driven, continuous effort to eliminate waste, with the goal of creating value, in which, customers' satisfaction should always be the primary goal [13]. Yet, Baines et al. first mention the relation between the PSS concept and lean manufacturing in 2007 [14] nearly a decade after the introduction of the PSS term [15].

Lean was primarily conceived as the practice (or group of practices) for eliminating and avoiding muda (wastes), adding more value to products and processes [16]. Muda reduction can be achieved by the implementation of lean principles and tools in the whole business environment. Several lean manufacturing practices are described in [17], such as the well-known TPM (Total Productive Maintenance) and JIT (Just-In-Time). The continuous monitoring of the KPIs can contribute to waste elimination, better process control, efficient manpower utilisation, and employment of flexible systems [2].

In the literature, it is very common to find the term Lean Rules conflicted with the term Lean Practice [18]. Usually, the term Lean Rules is used to describe teaching procedures about Lean philosophy [19,20]. However, there is a significant distinction between Lean Rules and Lean Practices. Lean Practices have been established many year ago [21,22], while Lean Rules first appeared in 2010 [18] as a new concept and its definition has been added very recently according to the following paper [23]. Particularly, according to the definitions, lean practices are specific tools that express a general philosophy that should govern the company and the production process, guiding the company towards leanness, while lean rules express straightforward instructions and actions, usually by using appropriate imperative verbs.

In general, the amount of literature work devoted to the combined Lean PSS ecosystem is limited, while most of the existing works focus on state of the art analyses. Specifically, after an extensive literature review, Sassaneli et al., identify which aspects of Lean thinking have already been applied in PSS development, and outline gaps for potential research, such as the definition of what is waste and value in a PSS design process [24]. Elnadi et al., bridge some gaps between Lean Thinking and PSS by focusing on the existing challenges, such as the understanding of leanness, definition of wastes, and the nature of the Service Process [25]. Also, a Lean PSS framework, along with a description of the fundamental elements which characterise Lean Production and Lean Service operations, is proposed in [26]. Two best-in-class lean PSS companies (Toyota Motor Italia and Alpha, Italy) are examined in order to analyse PSS activities under the aspect of Lean Thinking. A KPIs evaluation model is proposed in [27], which measures the degree of PSS leanness for UK manufacturing industries, through the definition of lean criteria. Similarly, in [8], KPIs for PSS design evaluation, related to leanness among others, are collected and classified.

In addition to the KPIs monitoring, context sensitivity tools would also be capable of supporting the PSS design phase. However, the adoption of context sensitivity tools during PSS design has not been sufficiently examined yet [28]. The basis for context-aware applications is a well-designed Context Model (CM). A CM enables applications to understand the user's activities in relation to situational conditions. There are various types of context-aware systems. In general, a context-aware system follows four steps

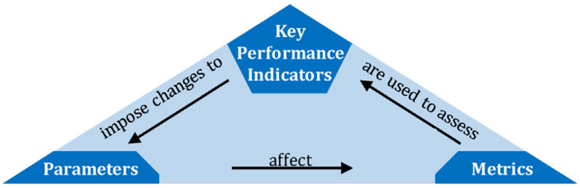


Fig. 2. The triangular KPIs monitoring procedure.

to fully enable context-awareness [29]: (i) acquisition of context information, (ii) storing acquired context information into a repository, and (iii) controlling the abstraction level of context information by interpreting or aggregating context data. An ontology-based approach is presented by Akmal et al., which can determine the similarity among two classes using feature-based similarity measures that replace features with attributes [30]. Also this approach is evaluated against other existing similarities and is illustrated in a case study on Product-Service Systems design problems. Moreover, Annamalai et al., propose an initial structure of PSS ontology by separately identifying the existing taxonomies of product and service ontologies and by identifying the root concepts of a Product-Service System through interviews with experts [31].

To summarise, in the abundance of literature dedicated to Lean thinking, there is a lack of comprehensive lean design methodologies, as well as tools for automatically providing lean rules in order to guide manufacturing decisions. Structured lean rules provision that guide each PSS lifecycle stage, aiming to reinforce the leanness of the design solutions, are not adequately investigated [32]. Also, no contribution has clearly and systematically identified the typical waste types (w) in a PSS design process, while the definition of what is a value-added activity is often vague [24]. Literature work associated with real-time monitoring of KPIs for evaluating PSS is sparse. As recent research shows [9], only limited number of papers related to PSS use KPIs for evaluation and amongst them, only some of them are associated with real-time monitoring. There is limited work on KPIs for the evaluation of PSS leanness [8,27], but it remains restricted to static calculations. Among the few contributions on Lean PSS, none provides a comprehensive methodology for evaluation and lean rules provision, while few works mention the continuous improvement of the PSS design via continuous monitoring of KPIs [33,34].

3. Methodology for lean rules extraction via KPIs monitoring

The proposed methodology exploits real-time monitoring of KPIs, to automatically extract lean rules (LRs) for PSS improvement. An ontology model is demonstrated as the background context model of the proposed methodology. The methodology is consisted of seven steps illustrated in Fig. 1, and briefly are described below:

STEP 1: The first step of the methodology is associated with the selection of appropriate KPIs by an organization in order to monitor the status of their goals and the degree of the targets' achievement. Each KPI has a mathematical formulation which is composed explicitly of metrics and implicitly of parameters. The interrelation between KPIs, metrics, and parameters is illustrated in Fig. 2. Weights are defined for each metric, once the KPI is decomposed to its metrics. The weights are defined by the company's experts, followed also by analysis of historical data captured by the company, in order to represent their objectives and goals.

STEP 2: The metrics of Step 1, via an appropriate ontology-based model, are associated with one or more of the following: (i) typical waste types that could be caused, which could fall in the categories of transportation, inventory, motion, waiting, defects, over-processing, and over-production (ii) PSS lifecycle phases which could be affected, and (iii) the well-established lean practices that could be used for consulting in order to avoid wastes and to increase the value

STEP 3: Once each metric is associated with a number of typical wastes, a weight (Wwi) is calculated for each metric, using the appropriate given formula (see Section 3.2). The definition formula of the Wwi, is based on the number of waste types (w) that contribute to a certain metric.

STEP 4: For every initially selected KPI, and considering the calculated weights of its metric that is composed, a Total Leanness Index (TLI) is defined via given formula (see Section 3.3).

STEP 5: KPIs monitoring via wireless sensor network. Once the TLIs are defined in Step 4, the proposed monitoring system provides the required input in order to calculate them.

STEP 6 Based on the monitoring results and the TLIs calculation of Step 4, a plot is created showing the interaction between the different TLIs and parameter values. The intersection point of the TLIs is dictated based on a pair of points created on the plot area after several iterations. The area around the intersection point denotes the range of the parameters values inside which the performed operations are Lean. The selection of the range of the parameter values is performed while taking into account quality and manufacturability constraints.

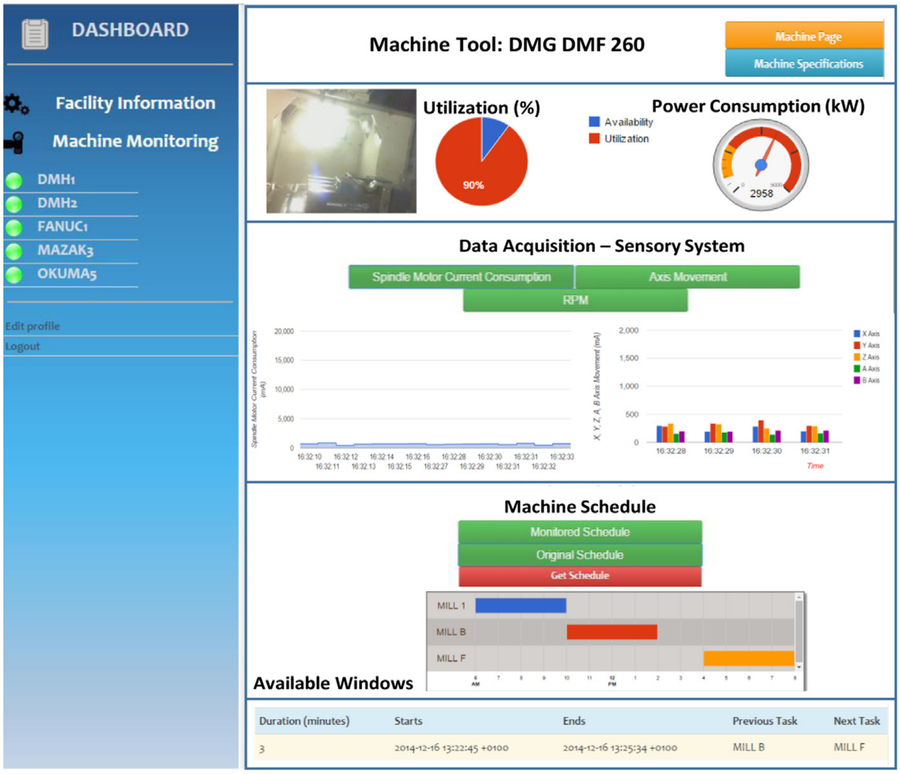
STEP 7 Once the lean area is dictated considering Steps 1–6, a set of lean rules is provided in an automated way, including recommendations and specific actions that should be followed by the company. The recommendation occurs after the correlation of the defined metrics with the PSS lifecycle phases, the typical wastes, as well as the Lean practices. In addition to that, specific actions are provided to the user in order to maintain the performed operation inside the Lean area.

The detailed description of these 7 steps will be presented in the next sections.

3.1. Mapping of metrics with PSS lifecycle stages, lean principles, and typical wastes (steps 1 & 2)

As it has been mentioned before, the initial step of the proposed methodology is the selection of the KPIs, and their decomposition to metrics and consequently to parameters. Following the previous concept, and based on the fact that value of metrics are affected by various parameters, the "Triangular" KPIs monitoring procedure is introduced (Fig. 2), which will be adopted in our methodology. User-defined weights are placed to each metric and are used to appropriately define the Leanness Index (*LI*). Commonly, the user-defined weights are strongly related to the company's objectives. Particularly, the extraction of these weights (Wmi) that correspond to each metric, are based on the company's needs and requirements, after analysing historical data obtained by the monitoring system, and on the experience of the company's experts.

Finally, using appropriate ontology-based context model, which will be presented in detail in Section 4, the metrics that contribute to the calculation formula of KPIs are then associated with the PSS lifecycle phases where their measurements are derived from, one or more typical waste types (*w*) that it can generate, and finally, with one or more Lean practices [35] which can be utilised to establish a leaner thinking in manufacturing activities. PSS lifecycle phases that are considered in the ontology model vary according to the different PSS design approach. For example, according to Rese et al. [36], the PSS lifecycle could comprise: planning, development, implementation, delivery and use, and closure. Alternatively, according to Neves-Silva et al. [37], a more service-oriented PSS lifecycle includes the phases of: concept, solution design, service implementation & product manufacturing, integration, distribution & sales, use & disposal. As lifecycle phases vary according to the perspective that they are considered, in the proposed work and based



Duration (minutes)	Starts	Ends	Previous Task	Next Task
3	2014-12-16 13:22:45 +0100	2014-12-16 13:25:34 +0100	MILL B	MILL F

Fig. 3. Monitoring via WSN.

on the selected case study, three life cycle phases were considered, namely the Design, the Manufacturing, and the Maintenance. In the proposed approach, the selected lifecycle phases are defined in the ontology model and are correlated with the metrics of the different KPIs. As a result, once the TLIs are calculated, the lean area is defined, and the proposed approach provides several recommendations related to lifecycle phases, Lean practices, etc.

3.2. *Definition of leanness weights (step 3)*

For each metric ($M_1,\ldots,M_n$), a leanness weight is calculated based on the number of waste types (w) that the metric affects. This weight is within the range of [0,1] and is calculated via formula (1):

$$Ww_i = \frac{\sum_{j=1}^{N} \lambda_{w_j}}{N} \tag{1}$$

where $i = 1,..,n$ is the integer number that denotes the used metrics, $j \in$ [1–7] index represents each w (Fig. 1), N is the total number of *waste typ* (here N = 7), and λ_{w_j} takes a value of one if the metric causes generation of waste, and a value of zero otherwise.

3.3. *Total leanness index (step 4)*

For each KPI, the TLI is defined as the dot product between the lean index (LI) vector, which represents the index of each w, and the unit vector $k = (\mathbf{k}_1, .., \mathbf{k}_n)$ that denotes the used metrics:

$$TLI = \overline{LI} \cdot k \tag{2}$$

where,

$$LI = (W_{m1} W_{w1} f_1(M_1)\,\mathbf{k}_1 + \ldots + W_{mn} W_{wn} f_n(M_n)\,\mathbf{k}_n) \tag{3}$$

and the LI is normalised using Eq. (4), which normalises cost criteria, i.e. criteria that need to be minimised, within the range of [0,1] [38].

$$\overline{LI} = \frac{LI - LI^{\min}}{LI^{\max} - LI^{\min}} \tag{4}$$

TLI is scalar since it is resulted by the doc product of two vectors. Moreover, the norm of each vector that constitutes the LI vector represents an index, which measures the leanness with respect to each w. This representation is useful in order to identify which w affects the *TLI* of the system and in which degree.

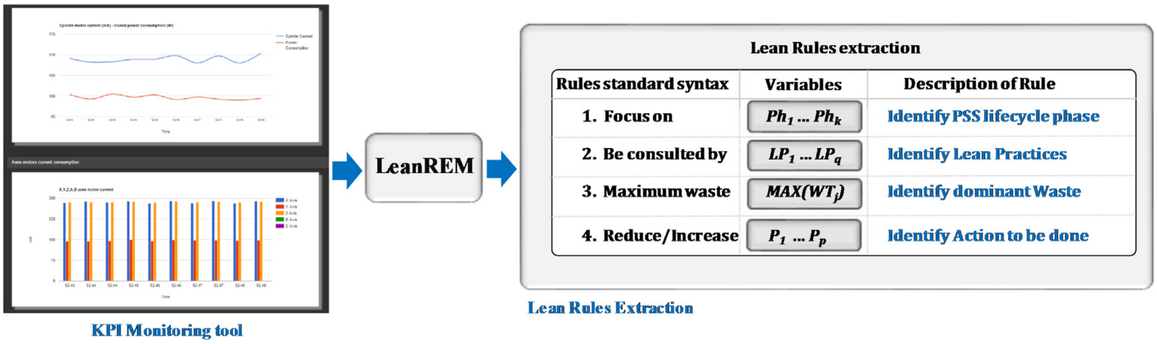
3.4. *Data acquisition via wireless sensor network (step 5)*

In order to close the loop of the proposed methodology, a monitoring module has been implemented using a Wireless Sensor Network (WSN) [39,40]. The monitoring module consists of three main components, namely the hardware device and the sensors, the WSN, and the software application [41].

The sensory hardware consists of current and voltage sensors and a Hall effect speed sensor for angular velocity measurements. The current and the voltage sensors monitor the overall energy consumption of the machine tool as well as the current of the main drives. Specifically, the current of the motors that drive the spindle and the axes and the current of the mains phases as well as the revolutions per minute (RPM) of the spindle are measured. The sensors collect current and RPM measurements with a frequency of 4 samples per second (Fig. 3).

The WSN is developed based on the ZigBee standard [43], which operates on the IEEE 802.15.4 physical radio specification. The security of the transferred data is considered a main factor during the implementation, and as a result a set of security policies that rely on the AES 128b encryption algorithm are used.

Once the data (values of metrics) have been captured by the hardware, they are transmitted via the WSN to the web database. An information fusion technique, combining the Analytic Hierarchy



Rules standard syntax	Variables	Description of Rule
1. Focus on	$Ph_1 \ldots Ph_k$	Identify PSS lifecycle phase
2. Be consulted by	$LP_1 \ldots LP_q$	Identify Lean Practices
3. Maximum waste	$MAX(WT_j)$	Identify dominant Waste
4. Reduce/Increase	$P_1 \ldots P_p$	Identify Action to be done

Fig. 4. Structure of automatically extracted Lean Rules.

Process (AHP) with the Dempster-Shafer Theory of Evidence [44], is employed to calculate the values of the selected KPIs. The software application is designed and developed for multiple user roles, including the machine tool operator, the production manager, and the maintenance expert. The machine tools operator provides the system with information, including the machine tool status, the running task, the machine tools breakdown events and the cutting parameters of a process.

3.5. Identification of lean area (step 6)

Based on the monitoring results and the TLIs calculation of Step 4, a plot is created showing the interaction between the different TLIs and parameters values. The intersection point of the TLIs is dictated based on a pair of points created on the plot area after several iterations. The area around the intersection point denotes the range of the parameters values inside which the operations that are performed are Lean. The selection of the range of the parameters values is performed taking into account quality and manufacturability constrains. The TLIs calculated for the selected KPIs are checked for the extraction of Lean Rules (*LRs*). *LRs* are automatically produced once the trade-off solutions have been found (intersection area of all *TLI* curves) after a sufficient number of iterations of Steps 1–6. More specifically, for each iteration (after an increase/decrease of a parameter value) and for each *TLI*, a pair of points are created on the plot area, and are linearly interpolated. This procedure is repeated until the pair of points converge i.e. the interpolated values are close to one another. This area offers trade-off solutions that must be reached to improve performance. Outside this area, an improvement for a certain KPI, in terms of leanness, could cause a deterioration of the leanness of another KPI.

3.6. Lean rules extraction (step 7)

Once the lean area is dictated considering the Steps 1–5, a set of lean rules is provided in an automated way, including recommendations and specific actions that should be undertaken by the company. Particularly, the recommendation occurs after the correlation of the defined metrics with the PSS lifecycle phases, the typical wastes, as well as the Lean practices. In addition to that, specific actions are provided to the user in order to retain the performed operation inside the Lean area. The possible structure for the automated generation of LRs is depicted in Fig. 4. The first type is associated with rules about the PSS lifecycle phase which affects the calculation of the selected KPIs. The second one is associated with the lean practices and more specifically, with a pool of 150 lean practices that the design can follow. The third one is associated with the identification of the dominant waste regarding the procedure, and the last one is associated with the certain actions that should take place in order to improve the leanness of PSS. All the aforementioned *Parameters* (P_1,.,P_p), *Metrics* (M_1,.,M_n), the *Lean Practices* (LP_1,.,LP_q), *PSS lifecycle stages* (Ph_1,.,Ph_k), and the type of Lean Weights (WT_1,.,WT_7), are connected via ontology, which will be described in detail in the following section.

The proposed ontology could be used by a context sensitivity algorithm, in order to guide the automatic lean rules extraction, triggered by a fully-defined KPI. According to relevant research, the ontology-based context modelling based on ontologies, seems to be the most appropriate for industrial use, and especially for the PSS design phase [28]. The present paper demonstrates a context model that could be considered for any context sensitivity tool.

4. Ontology model and lean rules extraction

The execution of the aforementioned main steps that comprises the automatic LeanREM (Fig. 1), is carried out through an ontology context model illustrated in Fig. 5. The ontology is developed as a conceptual data model for the representation of technical information. More specifically, KPIs are associated with Metrics that are used for the calculation of KPIs. The Metrics have weights ($Wm_{i,}$ Ww_i), and are affected by Parameters. The selected Metrics and Parameters belong to one or more PSS lifecycle phases, contribute to one or more typical wastes (TW_j), and are associated with one or more Lean Practices.

5. Case study

A real-life case study from a mould-making industry is applied in order to validate the proposed methodology. The shop-floor of the case study consists of 8 job-shops, which include 14 work-centres that are formed by 40 individual resources in total (Fig. 6). The resources include on one hand high precision CNC machines that are capable to perform milling, drilling, turning, electro-discharge wire cutting, sinking, grinding, tapping, roughing, polishing, and hardening operations, and on the other human operators that perform manually operations of design, fitting, assembly, measuring, and polishing (Fig. 6). The hierarchical model of the production facility is depicted in Fig. 6.

The case study is divided into two levels, namely the shop-floor level, where the extraction of *LRs* for effective and lean machining is pursued, and the factory level, which focuses on the extraction of *LRs* for reaching more efficient, eco-friendly, and lean production strategies. Appropriate KPIs are selected to be measured in each validation level. These KPIs are conflicting in nature, so that a trade-off is attainable. In both cases, the monitoring system (Section 3.5) is installed on the machine tools of the shop-floor, while mobile devices are used by machine tool operators, production managers, and maintenance experts for visualisation and reporting purposes.

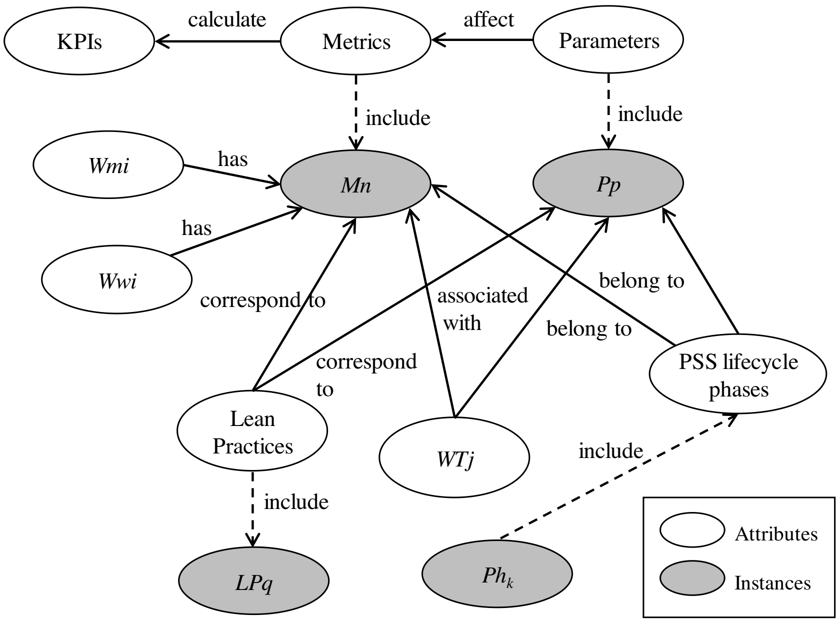


Fig. 5. Ontology model for KPIs to guide the Lean Rules extraction methodology.

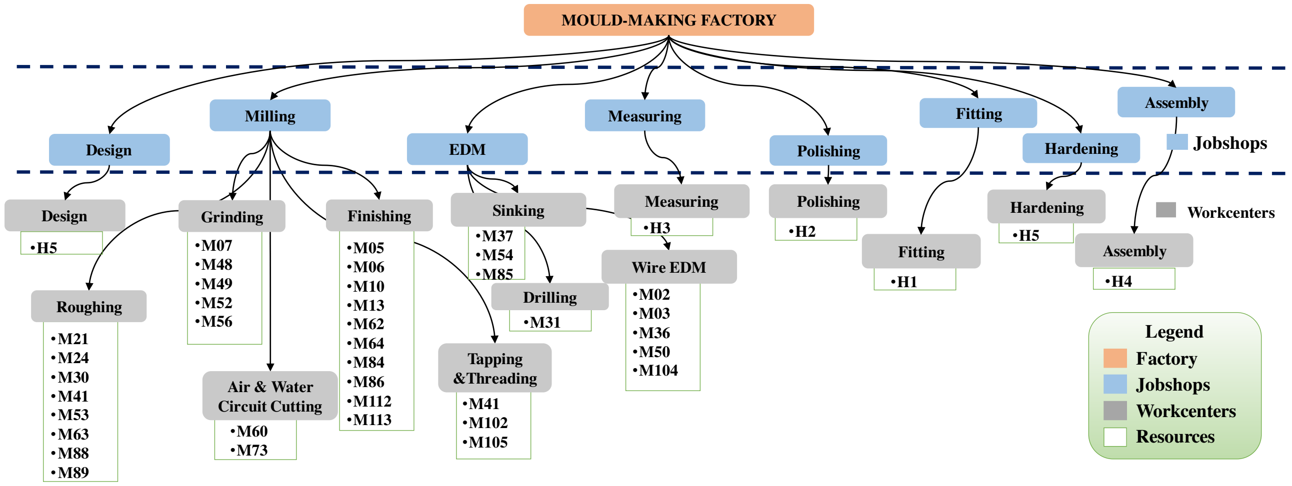


Fig. 6. The facility model of the mould-making job-shop.

5.1. Shop-floor level validation

At the shop-floor level, the milling machine tools are selected, since in mould-making industry they are key for productivity and are utilised in most daily operations. Regardless, the methodology can be applied to multiple machine tools and manufacturing processes. This case targets the creation of *LRs* which would lead to a reduction of the environmental impact of machining, through a fine-tuning of cutting parameters and conditions. The selected KPIs are the Energy Consumption (EC) of the machine tools and the Machining Time (MT) of the processes. To calculate MT, the actual machining time is measured, which also constitutes the single used metric (see Fig. 2). The metrics that contribute to the EC KPI are the power intensity, the power coefficient, and the voltage. Power coefficient and voltage are constants that are dictated by the machine tool. Thus, the power intensity is the variable metric. The cutting parameters, which influence EC and MT KPIs on a specific machine tool, are the feedrate, the cutting depth, the spindle speed, the cutting speed, and the selection of cutting tools.

Following the steps of the methodology, each metric is assigned a *Wmi* weight, denoting its relative influence on the KPI. As it has been mentioned before, the weights (*Wmi)*, are user-defined and reflect the company's objectives. At the present case, the KPI of energy consumption (EC) is calculated as the product of metrics: (i) power coefficient, (ii) voltage, and (iii) power intensity. Decomposing these KPIs to these three metrics, only power intensity holds an important role for the company and makes sense to be investigated, therefore the power intensity is given a weight of 0.8 in order to increase its involvement, and subsequently the power coefficient and voltage metrics are assigned the remaining percentage, equally divided. Since only one metric contributes to MT, namely the actual machining time, it is calculated to be *Wmi = 1*. In our case study, the weights that are defined to the metrics of the KPIs are selected following the experience of company's experts. This experience is based on the analysis of the historical data stored in the company. Then, each metric is correlated with one or more typical wastes. Power intensity generates Over-processing and Motion wastes, and the actual machining time generates Waiting wastes.

Table 1
Experimental results from the monitoring system.

No of Experiments	Feed Rate (mm/min)	Machining time (sec)	Power consumption (VA)
1	40	437	1501
2	60	291	1521
3	80	224	1528
4	100	184	1538
5	120	153	1542
6	140	133	1545
7	160	122	1547
8	180	115	1552
9	200	95	1556
10	220	82	1558
11	240	71	1562
12	260	68	1565
13	280	67	1568
14	300	66	1570
15	320	64	1573
16	340	58	1578
17	360	56	1582
18	380	55	1588
19	400	54	1590
20	420	53	1600
21	440	52	1610
22	460	50	1619
23	480	49	1625
24	500	48	1630
25	520	46	1638

Moreover, the power intensity metric is given a *Wwi* weight of 0.28, and the actual time of machining metric a weight of 0.14 (Eq. (1)).

The leanness index (*LI)* is then calculated for each one of the EC and MT KPIs using Eq. (3). For example, the Leanness Index and total leanness index for the KPI of the energy consumption is shown below:

$$\overline{LI} = 0.28\ \left(I(p_p)\cdot\mathbf{k}_1 + V\cdot\mathbf{k}_2 + \cos(\varphi)\cdot\mathbf{k}_3\right) \tag{5}$$

$$TLI = 0.28\ \left(I(p_p) + V + \cos(\varphi)\right) = 0.28\cdot I(p_p) + C \tag{6}$$

A milling process on an aluminium workpiece using a 10 mm diameter cutting tool is examined. The cutting depth is set to 2 mm and the spindle speed to 2000 rpm. The feedrate (f_d) is altered within the range of 40–520 mm/min (Table 1). The range of the feedrate presented in the case study has been selected to respect the quality specifications, in order to not reduce the quality of the product. This feedrate range of course is altered by the material and the type of the machine that has been used. The present work is reduced only in the using of 2 KPIs for applying the methodology, while as it is already mentioned in the conclusions paragraph, future work will comprise more than two KPIs for the implementation of the methodology. Moreover, in the present study two production-oriented different sets of KPIs have been selected, one from the strategic and one from the operational level of a production system. To obtain a leaner process, the *TLI* is calculated (Eq. (2)) at each iteration of the methodology and *LRs* are generated in order to drive the refinements of the next iteration, mainly regarding the fine-tuning of feedrate. This case study aims to the creation of LRs which would lead to a reduction of the environmental impact of machining, through a fine-tuning of cutting parameters and conditions. As most of the companies and specifically the SMEs are using electric power to operate, which highly increases their operational cost, the reduction of the electric power is of high importance for them [42].

Once the improvement of one *TLI* is accompanied with a deterioration of another *TLI*, the methodology terminates and the desired trade-off is found. Fig. 7 shows the relationship between EC and MT for 25 loops. As expected, as the feedrate increases, MT decreases, while EC increases.

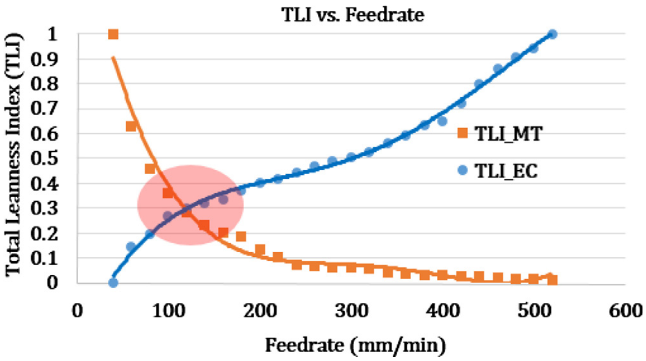


Fig. 7. Total Leanness Index for Machining Time (TLI_MT) and Energy Consumption (TLI_EC) vs. feedrate.

Table 2
Monitoring Results for MC and MRT KPIs.

No of Maintenance Report	MC (€)	MRT (min)
0	50	1
2	35	2
4	25	4
6	20	6
8	19	8
10	18	10
12	17	12
14	16.5	14
16	16.4	16
18	16.1	18
20	16	20

The area around the intersection of the two curves provides a trade-off between the two KPIs. These targeted values are used by the algorithm as a termination condition. The automatically generated *LRs* during these iterations are:

5.2. *Factory level validation*

The factory level case concerns the extraction of *LRs* related to the factory's maintenance strategy, which is a representative example of product-oriented PSS [14]. The KPIs used are the Maintenance Cost (MC) and the Maintenance Reporting Time (MRT). MC has as metric the cost of repairs and MRT has as metric the repair time. The parameters that influence the KPIs are the number of reports and the maintenance time. In a similar way as in the shop-floor case, the *Wmi* of both metrics is 1. Regarding the correlation of the repair cost metric with the typical wastes, a *Wwi* of 0.42 is assigned, since repair cost contributes to Defects, Motion, and Over-processing wastes. The *Wwi* of the repair time is 0.28, as it contributes to Motion and Over-processing wastes. The *TLIs* for the MC and MRT KPIs are calculated by (1), and are normalised using (4).

The operator, using the mobile device, can compile and send to the maintenance department up to 20 reports per day. The monitoring system measures the reporting time required and the repair costs (Table 2).

Fig. 8 is generated after 11 iterations. In the graph, the intersection area in which maintenance becomes leaner is also highlighted.

5.3. *Lean rules extraction for shop-floor and factory level*

Based on the analysis presented in the previous sections related to the TLI on shop-floor and factory level, the corresponding extracted Lean Rules are presented in Fig. 9.

Following Fig. 9, SMED (Single Minute Exchange of Dies) is proposed in order to reduce setups (changeover) time, and OEE (Overall

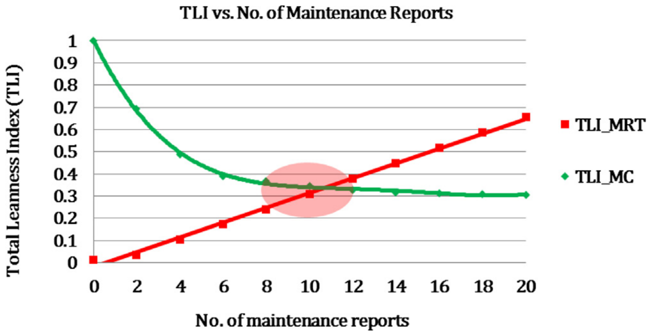


Fig. 8. Total Leanness Index (TLI) for Maintenance cost (TLI_MC) and Maintenance reporting time (TLI_MRT) vs. no. of maintenance reports.

Equipment Effectiveness) is the framework or measuring productivity loss for a given manufacturing process. Three categories of loss are tracked: availability (e.g. downtime), performance (e.g. slow cycles), and quality (e.g. rejected). SBL (six big losses) includes six categories of productivity loss that are almost universally experienced in manufacturing (setup, breakdowns, small stops, reduced speed, start-up rejects, and production rejects). PDCA (Plan, Do, Check, Act) comprises an iterative methodology for implementing improvements. TPM is a lean practice that advises towards the creation of a shared responsibility for equipment and encourages greater involvement by plant floor workers. Its application can improve productivity, increase up time, reduce cycle times, and eliminate defects [45].

The proposed methodology attempts to extract comprehensive rules to guide companies towards lean. The relationship between the extracted rules and the lean practices (TPM, OEE, SMED) is achieved through an appropriately defined ontology-based context model. In existing literature, there is a clear distinction among lean principles, practices, as well as lean rules [18]. The actual challenge has been to diffuse Lean Thinking into the whole of the company, by defining specific rules that should be followed and are based on the generic lean practices [46]. Towards that, the presented methodology, through the ontology-based model and the KPIs monitoring can provide specific lean rules-actions that should be followed by the company in different operations and can also recommend in which well-established lean practices, and typical wastes of PSS lifecycle phases should the company focus on.

The main contribution of the proposed work is summarized in the following points:

- To support companies that are moving towards lean philosophy in taking specific actions (Lean Rules), and diffuse lean thinking into the whole of the company, considering data and KPIs from different legacy systems
- To provide an ontology model though which the different PSS life cycle phases, the typical waste as well as the lean practices will be correlated with the KPIs and their metrics.
- To identify and specify the lean areas in which the different parameters of the operations should be in, in order to be lean.
- To enhance the awareness of the different roles in the company not only by providing them instructions, but also by supporting them in understanding how the results of the different KPIs that are measured in an enterprise can provide meaningful insights.

5.4. Lean rules extraction for multiple KPIs and multiple parameters

The case study presented above provides the lean rules extraction using two different sets of KPIs and two independent parameters (feedrate, and no. of maintenance reports). The KPIs were selected based on the requirements of the company and the main data sources that were provided, considering also the proposed monitoring system.

This section attempts to investigate two generalized scenarios in order to complete the methodology. These scenarios consider two different situations: (i) more than two KPIs in a single affected parameter, and (ii) more than two KPIs with more than one parameter.

Regarding the first scenario, where there are two or more KPIs and consequently two or more TLIs with a single affected parameter Fig. 10 represents a graphical methodology to support the selection of the appropriate value or value range of the specific parameter, that gives a leaner design solution. Specifically, as Fig. 10(a) represents, in the case of two common points within three TLI curves, the central point of the line segment is selected as the better solution for the parameter. Moreover, by projecting the points in the horizontal axis, the area of the accepted variance of the parameter to achieve leanness is found. Otherwise, when the common points are three, as illustrated in Fig. 10(b), then a triangle is created, and the centroid of this triangle is selected as the leanest solution. Moreover, the projection of the lower and upper values of vertices to the horizontal axis defines the area of the accepted variance of the values parameter. Finally, the last investigated case is when there are more than three common points, as depicted in Fig. 10(c). In this case the created area, by joining all the vertices, could be convex (blue – dashed area) or concave (red area). Based on fundamental

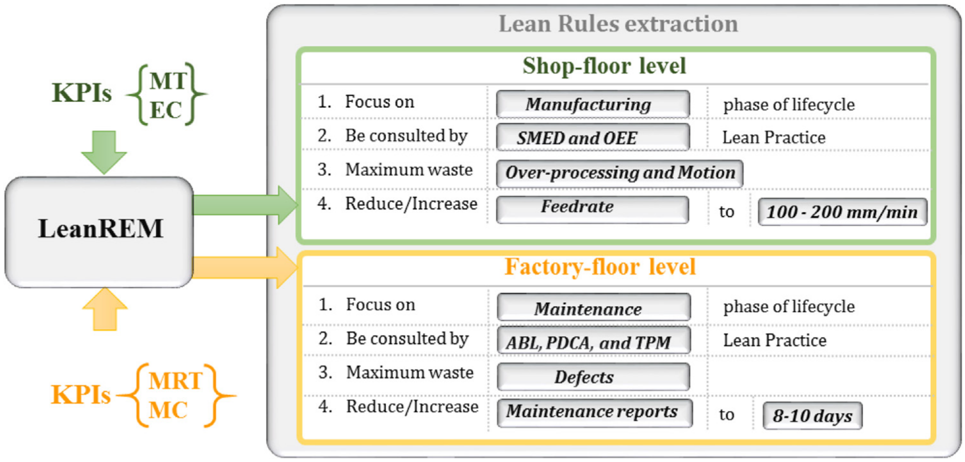


Fig. 9. Lean rules extraction based on four KPIs; Maintenance Time (*MT*), Energy Conception (*EC*), Maintenance cost (*MC*) and Maintenance reporting time (*MRT*).

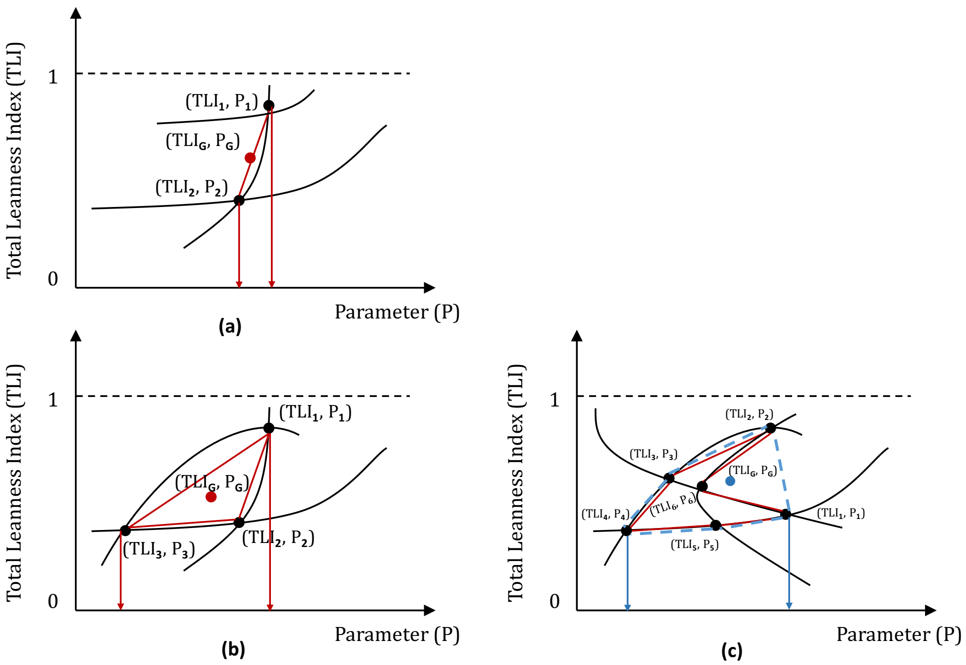


Fig. 10. Graphical methodology for the selection of appropriate variance of parameter when there are more than two KPIs and TLIs consequently. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

topology, a concave polygon has at least one reflex interior angle, while a convex polygon is a simple polygon (not self-intersecting) in which no line segment between two points on the boundary ever goes outside the polygon. These two areas presented in Fig. 10(c) are equivalent, because the calculation of the centroid give the same pair of points. The generalised calculation formula that gives the centroid point for all the aforementioned cases, is the following:

$$(TLI_G,\ P_G)=\left(\frac{1}{n}\sum_{i=1}^{n}TLI_i,\ \frac{1}{n}\sum_{i=1}^{n}P_i\right) \tag{7}$$

where,

TLI_G: the value of the total leanness index in the centroid
P_G: the value of the parameter in the centroind
n: the number of common existing points.

Regarding the second case (ii), where there are more than one affected parameters to TLIs, two different situations occur: (a) there are m independent parameters, and (b) there are m dependent parameters. The first case (a) is simple since there is no dependency among the parameters, so the above presented procedure (the created plots) is repeated in the same way. Fig. 11 shows the selection procedure of *m* independent parameters when there are many KPIs (consequently TLIs), keeping in the plot only in the created area from the common points of TLI curves.

However, the case (b) is more complex since the dependency between two or more parameters could be linear, polynomial, exponential, logarithmic or a combination of the previous. In cases where the parameters have a simple relationship, to find the value of only one parameter we can easily calculate the others by solving an equation or a system of equations. On the other hand, when the relation of parameters is very complex, only specialized computational methods and heuristics algorithms could give an exact or an estimated solution for the determination of parameter values.

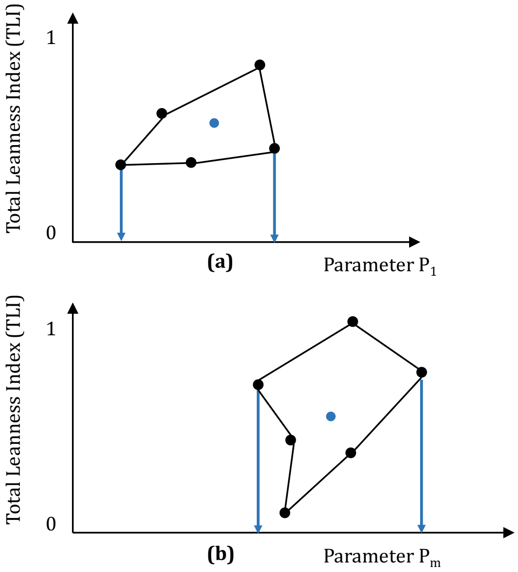


Fig. 11. Parameters values selection for m independent parameters.

6. Conclusions

The proposed work aims to transform an industry's functions towards producing leaner PSS offerings through gradual improvements on both process and factory levels. The automatic generation and suggestion of lean rules and practices in each iteration of the methodology (LeanREM), via real time monitoring of Key Performance Indicators (KPIs) and ontology model, instils over time the lean philosophy in the factory, and wasteful activities are steadily avoided, thus increasing efficiency.

In order to validate the above methodology and its main functionalities, a real case study is used from a mould-making SME. The mould-making industry is trying to move towards Lean Thinking, and specifically through energy consumption reduction and efficient maintenance planning that will reduce their costs. Following the main requirements of the SME concerning energy consumption reduction and accurate maintenance planning, the two different levels of validation were designed. The proposed methodology was applied to both levels and the main output is the identification of the Lean area which should be taken into account in order to render the operations leaner. The low-level instance examined the leanness from a machine perspective, and improvement rules where used in order to diminish wasteful machining practices and reach a trade-off between machining time and energy consumption. The high-level instance considered the factory as a whole and focused on enhancing the PSS of the mould maintenance service. At first glance, the results of the validation are obvious, however the main outcome through these results is the identification of the Lean areas. Though the proposed approach, the Lean area in which the operations can be lean is suggested, offering the human operators meaningful and useful insights so as to apply lean rules considering always the quality and manufacturability constraints. As a result, for the purpose of providing quantitative information about the overall benefit of the approach, further validation is needed in order to measure the overall energy consumption reduction as well as the overall performance in maintenance time. This is in the scope of future work, measuring the overall performance of the approach and also enhancing it with new paradigms in order to validate its applicability.

Finally, it is introduced a graphical methodology aiming to drive the selection of appropriate value parameters, when there are multiple KPIs and TLIs consequently. Moreover, a short discussion about what happens when there are many affected parameters independent or depended is included.

The future work will focus on addressing the limitations of the methodology. Specifically, future work will further investigate the existence of multi-KPIs/TLIs with the concurrent existence of and multi-depended affected parameters. Such an analysis will be incorporated as a separate step in the methodology. Moreover, Finally, the improvement of leanness on a supply chain level is not investigated currently, yet the potential benefits from waste elimination on a strategic level can be substantial. KPIs related to the supply chain's performance will therefore be incorporated.

Acknowledgements

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