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Scope and topics

Advances in Production Engineering & Management (*APEM journal*) is an interdisciplinary refereed international academic journal published quarterly by the *Production Engineering Institute* at the *University of Maribor*. The main goal of the *APEM journal* is to present original, high quality, theoretical and application-oriented research developments in all areas of production engineering and production management to a broad audience of academics and practitioners. In order to bridge the gap between theory and practice, applications based on advanced theory and case studies are particularly welcome. For theoretical papers, their originality and research contributions are the main factors in the evaluation process. General approaches, formalisms, algorithms or techniques should be illustrated with significant applications that demonstrate their applicability to real-world problems. Although the *APEM journal* main goal is to publish original research papers, review articles and professional papers are occasionally published.

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An implementation of lean scheduling in a job shop environment

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A B S T R A C T

Globalization has demanded innovative manufacturing and continuous improvement in order to stay competitive. This need has compelled the manufacturing world to devise strategies for producing cost-efficient parts without compromising quality. The Toyota Production System was at the beginning of such initiatives. It was successful in addressing cost through elimination of non-value-added time and quality by monitoring and controlling the productions of defective parts. Lean thinking originated from the Toyota Production System and inherited its concepts and methodology. In contrast to the Toyota Production System, the implementation of lean has been proposed in almost every domain of life. In the manufacturing domain it is a common misconception that lean is suitable for mass production only. This research has been built upon the belief that lean is for everything and has challenged this stereotype by implementing it within a job shop environment. A manufacturing industry was selected that was rebuilding battlefield tanks. The existing system was suffering delays and missing delivery targets due to uncertain and costly production. The proposed and existing systems were modeled and simulated using Arena 10.0 software. This work was successful in reducing the manufacturing-led time, work in process inventory and average cycle times with a reduction in cost and space utilization. Cost benefit analysis was performed showing that the proposed system would be beneficial after 1500 parts. We are further expanding our proposed approach towards the tool manufacturing shop in order to study the impact of lean and its suitability for scheduling in job shops.

A R T I C L E I N F O

Keywords:
Manufacturing
Toyota Production System
Lean thinking
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One piece flow
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1. Introduction

Manufacturing industry has gone through evolutionary changes in last few decades. Standardization and interchangeability has helped developing countries to earn their share of manufacturing due to lower labor costs. Competitiveness and economic challenges have diverted manufacturing activity from West to East. Industries with obsolete manufacturing systems are losing business due to excessive production costs and uncertain production delivery times. These factors have strengthened manufacturing industries in Eastern world [1]. Japan introduced innovative manufacturing system that was later known as Toyota Production system (TPS) [2]. This system believed in identification and elimination of seven critical wastes in production, supply chain and management processes [1]. Quality was the essence of TPS philosophy that helped it to revolutionize the manufacturing industry [1, 3]. Lean thinking is an off spring of TPS [3, 4]. Market challenges to manufacture at lower cost with less time and more throughput, paved way for lean manufacturing [4]. Lean manufacturing believes in systematic elimination of waste, relies on continuous flow concepts and customer pull. This management system overwhelmingly succeeds in satisfying customers on delivery, quality and price through elimination of non-value-added activities and wastes [3]. This manufacturing philosophy believes in elimination of wastes for entire supply chain and aims to provide good quality products through low processing and cycle times, and more responsiveness to customer needs [5]. With the success of TPS in Japan and a tremendous boost in Japan's manufacturing activity in 1970's, US manufacturers were forced to review their existing ford system and analyze the success story of TPS [3, 4]. Eventually, lean manufacturing motivated by TPS appeared in American factories [3]. It became important to get lean to stay competitive and succeed in challenging market place [4]. Value stream mapping, one piece flow, 5S system, quick changeover, Kanban, cellular strategy and total productive maintenance are tools of lean manufacturing to improve quality, cost and delivery [6].

Waste, in lean paradigm, is a non-value-added activity that puts extra burden on the customer and customer is definitely reluctant to spend on it [3, 4]. Overproduction is the worst in seven basic wastes in production activity. Lean thinking strongly opposed the concept of "make to stock" and stressed the need for "make to order". Overproduction results from over engineering, misuse of automation, poor scheduling, and just in case logic. Balancing the assembly line and adjusting the productivity may help to overcome this waste. Another important waste in manufacturing is long waiting times. This may occur due to saturation of work load on some workstations. Adjusting the process times and making the system flexible to cope with breakdowns may be helpful to eliminate this waste. Overproduction and long waiting times result in large work in process inventory. One piece flow strategy is an effective way to deal with this inefficiency of production system [7]. Long processing times and waiting times contribute to large work in process. Transportation is considered non-value-added activity and must be minimized to improve the cycle times of part production. This waste is resultant of poor facility design and layout and large batch sizes. This waste also contributes to larger work in process inventory. Undue motion of the work force, equipment and machines is another waste that causes larger lead times. This is also due to poor facility layout and improper location of machines and equipment. Avoiding the unnecessary movements may be helpful to reduce work in process and improve the lead times and reduce cycle times. Production of defective products is well known waste and efforts to curtail this waste are covered under the umbrella of quality management. Identification and fixing the defects is not the real purpose of quality management. Efforts should be to identify the causes of poor quality and adopt methods to eliminate re-occurrence of defects. Utilization of resources must be optimal and properly planned. Underutilized resources increase the cost of product and make the work in process (WIP) inventory larger [3, 7]. Ideally a production process must be free from these seven wastes. These wastes hamper the business performance and make the production activity expensive and costly. Lean manufacturing ensures elimination of wastes in the overall manufacturing process and helps to reduce the cost of production. Lean is concerned with improvement in entire process flow instead of one or more individual processes [1, 8].

Lean manufacturing is known for its success stories in reducing cost and improving the market share through better quality for mass production industries [4]. Our research is concerned with exploring the feasibility of lean in a job shop environment.

Maroofi and Deghan [9] has presented a conceptual framework for possible implementation of lean in job shop environment. Proposed model uses LET project that comprises business procedure management, supplier management, and value system management. They devised two phrased solution for supplier management using fuzzy logic and ant colony optimization. They suggested separate value stream map for each product due to high variety of products. Value stream map can be used for better scheduling of parts and can be helpful to eliminate wastes and non-value-added activities. Our proposed approach has addressed the same problem through modeling and simulation. Instead of proposing separate value stream map for each product, we have made necessary changes in the layout and reduced the waiting and queue times through sequencing of the parts. We provided one piece flow for process improvement and suggested re-arrangement of workstations.

Eng and Ching [10] claimed that lean is not suitable for all situations and presented quick response manufacturing as an alternative for job shop environment. They believed that quick response manufacturing is suitable for low volumes and high variety and can be successfully used to reduce critical path times. Our research was to challenge this stereotype and was successful in proving that lean can be used for high variety environment as well.

Assaf [11] used programme evaluation and review technique (PERT) to address the job shop scheduling problem. Processes were throughly studied and then author suggested new sequencing of processing using PERT. Author used parallel sequencing for independent processes and was successful to reduce the lead times. Our research also re-arrnages the workstations after thorough study of existing system. We used expert judgment to re-arrange our 10 workstations problem. Usability of PERT for large number of workstations cannot be denied but implementation will require formation of groups for different part families. This methodology is similar to already existing group technology and cellular manufacturing. We have used part and processes matrix instead of PERT to separate the part families.

Modrák and Semančo [12] presented the cell design methodology to transform job shop production process to lean. They defined decision making rules and principles to achieve One Piece flow for job shop. Similarly, we have devised the One Piece flow for our case study and implementation has resulted in achieving the WIP equal to workstations.

Irani [13] believes that there is no specific lean tool that is ideal for job shop. It is always better to blend these tools and methodologies to prepare a customized recipe, suitable for a specific job shop environment. Author has not provided any specific solution for the job shop and only discussed prospects and consequences of different methods and tools.

Djassemi [14] introduced three stepped lean implementation process. It constituted training, Kaizan continuous improvement and implementation. Author implemented this approach on pilot projects and identified the improvements made during continuous improvement phase. This approach was successful to reduce the overtimes by 37 % and improve on-time delivery by 11 %. This approach is altogether different from our approach. This approach relies on continuous improvement methodology and our research is concerned with elimination of wastes.

Section 1 outlines emergence of lean from Toyota Production System and brief review of lean in job shop environment. In section 2, we have briefly identified the common problems faced by job shops. Section 3 is about the performance criteria and measures used to compare lean with existing system. In section 4 and 5, we have introduced and explained the experimental set up and results. Section 6 is the last but not the least that concludes our research work and explains future directions.

2. Lean in job shop

Manufacturing is a business activity aimed at producing goods and providing services to satisfy humanly needs. Through value added physical and mental labor, raw material is transformed into useful product that satisfies the demands of customers. Such value addition activities are known as manufacturing process and overall combination of these processes makes a manufacturing system. Manufacturing systems can be either product oriented or process oriented. Process oriented processes provide continuous production and are known as continuous production systems whereas product oriented manufacturing processes are known as discrete part manufacturing. Discrete part manufacturing systems are further categorized as low, medium and high based on the quantity produced by an industry. There can be range of products being manufactured by an individual industry. This range of products can be either similar or different to each other. Range of products is known as variety and high variety limits the quantity of production. High variety results in low volumes of productions and low variety may guarantee high production [7, 15].

Job shop is a low volume high variety manufacturing environment. In order to produce range of products, a job shop requires highly skilled and versatile workforce and flexible manufacturing capability. Automation and specialization in some specific task are not supported in job shop environment. Job shops are characterized by fixed position layout, where product remains at single location during the entire production process. Workforce and equipment move to the fixed product for value addition activities. Ships, submarines, locomotives, aircrafts and battlefield tanks manufacturing are some typical examples of job shop environment having fixed position layout [7, 16].

Lean manufacturing can deal with missing order dates, high production costs, decline in market share and limited capacity. Is lean philosophy equally successful in job shop environment? We have selected a defense organization having job shop environment and manufacturing and rebuilding battlefield tanks. We found that Precision Defense Organization (PDO) is facing problems in:

- Manufacturing and rebuilding of sub-components of battlefield tanks well in time to ensure committed delivery of final product.
- Optimal utilization of resources with inability to identify bottleneck workstations.
- Determination of exact production capacity before making commitments with customers.

Middle management remains under tremendous pressure to meet unrealistic targets. Despite extra shifts and undue expenditure on overtime, targets are missed and linger on. Our focus was to determine the benefits of the utilization of lean thinking in PDO, because it is common misunderstanding that lean manufacturing is suitable for mass production systems only and will not be successful in job shop environment [17]. This work study was an endeavor to address these problems and ensure smooth production in job shop environment.

3. Performance measures and evaluation criteria

In order to determine the usefulness of our proposed solution for the improvements in existing system, we have identified some performance measures. These performance measures are:

1. Work in process (WIP) inventory
2. Manufacturing lead time
3. Average cycle time
4. Throughput/Productivity
5. Cost reduction
6. Work place area
7. Delivery commitments (mean tardiness)

3.1 Work in process (WIP) inventory

In process components in a system for some period of time are known as work in process (WIP) inventory. WIP is considered highly significant factor in production system as large size of WIP increases production costs. Optimally, the size of WIP should be equivalent to the number of workstations in the manufacturing system.

3.2 Manufacturing lead time

Time from release of an order to manufacturing of finished product is called manufacturing lead time and is inclusive of processing time, wait time, inspection and transportation time. Manufacturing lead time includes value addition and non-value addition times. Manufacturing lead times can be reduced after excluding all or some parts of non-value addition activities.

3.3 Average cycle time

In manufacturing lead times, the time spent on value addition activities is called cycle time. It is processing time to transform raw material into finished product and excludes wait, transportation and queue times.

3.4 Throughput/Productivity

Rate of production is termed as productivity or throughput for manufacturing activity. Work in process (WIP), manufacturing lead times and average cycle times are primary performance measures. Productivity is dependent upon these primary measures and can be termed as secondary performance measure. Manufacturing lead time (MLT) is inversely proportional to productivity. Higher MLT results in lower productivity and vice versa.

3.5 Cost reduction

An increase in productivity results in cost friendly manufacturing activity. We have selected this performance measure to compare the existing manufacturing system with the proposed. Cost reduction is the ultimate requirement of any business activity and its importance cannot be denied.

3.6 Workspace reduction

Another important aspect of lean manufacturing is to optimally utilize the space for manufacturing and production. We will review and compare the workspace utilization for existing and proposed system. Reduction in workspace can be guaranteed through elimination of seven wastes of production activity as described by Just In Time (JIT) and lean thinking.

3.7 Delivery commitments

Industries determine production capacity to commit delivery targets with customers. These commitments may be based on expert judgment of operations manager or modeling the existing system. We have found that PDO is committing the targets and deliveries based on their expertise and previous experiences. We preferred to model the existing system to determine the exact production capacity of PDO. We have identified lateness and tardiness as performance measures to gauge delivery fulfillment performance measure of PDO.

Lateness of a job is the difference between the due time and actual delivery time. Preferably, lateness should be positive or zero. In case of late deliveries and inability to meet targeted commitments, lateness may become negative. Ideally, occurrence of negative lateness should be avoided.

Tardiness of a job is the maximum value of lateness and is always negative. An occurrence of delivery commitment before the targeted deadline is called earliness and is not part of our performance measures.

4. Experimental study

A battlefield tank comprises three main mechanical assembling units, i.e., gun barrel, hull and turret. In our study at PDO, we have selected hull assembly for our experiment and analysis. Since PDO is busy in rebuild and manufacturing of battlefield tanks, we have selected hull rebuild and repair shop involved in repair of suspension and power pack parts and components as per original engineering manual (OEM), in hull assembly section of PDO. Overall process flow for rebuild of suspension parts is given in Fig. 1.

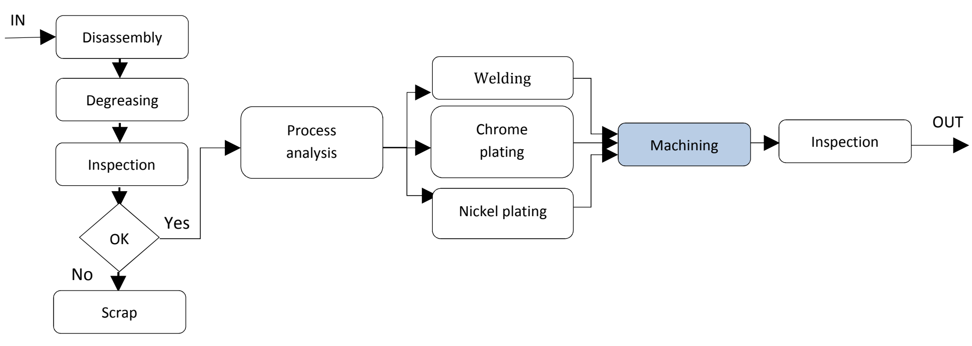

Fig. 1 Process flow of PDO job shop

Our research is concerned with the machining phase of suspension parts. These parts include balance arm, crank arm, sprocket hub, driven gear, driven shaft, final drive, idle wheel disc, left right supports, shock absorber blade and worm gear. An individual tank assembly requires 2 parts of each except balance arms and shock absorber blades. There is requirement of 10 balance arms and 4 shock absorber blades for typical Chinese and Russian origin battlefield tanks. Each part has different routing and processing requirements. These are highly and frequently wearing out parts in suspension and power pack assemblies of hull section in battlefield tanks. These parts delay the final assembly of hull section and contribute to overall delay in battlefield tank assembly. Shop floor involved in repairing of these parts is equipped with center lathes, gear lathes, radial drilling machine, broaching machine, vertical lathe, vertical and universal mills, broach, bench drilling machine, universal grinding machine and inspection cum bench fitting. These are those machines that are selected after making cells and groups of similar parts. Each part has different sequence of operations, e.g. sequence of operations for sprocket hub is, vertical lathe (turning), broaching, milling, internal grinding and for balance arm, sequence is turning, milling, cylindrical grinding, heat treatment, surface treatment and inspection.

Our proposed approach (Fig. 2) comprises three main phases. First phase is concerned with study of processes and layouts and identification of part families and formation of cells. Second phase is continuous improvement phase. In this phase, we re-arranged the workstations using the sequencing chart of parts in group such that there was no backward movement of the part during the processing. A part enters from one side of the cell, moves ahead and departs from the other side after value addition. We identified delays through analysis of waiting times, queue times, arrival times and processing times. Third phase implements lean thinking and uses quick changeover, total preventive maintenance, elimination of wastes and Kaizan methodologies. Using Kaizan continuous improvement methodology, we re-adjusted arrival times and reduced waiting times through increase in resources and provision of quick change over. We reduced processing time through improvement in time to failure and reduction of breakdown times. This helped us to establish One Piece flow in job shop.

We have used manufacturing simulation software Arena 10.0 [18] to model existing and proposed scenario of the PDO case study. Existing system has spaghetti layout with woven routing of parts for value addition processes. We have generated part families for these parts and re-arranged the placement of workstations to provide a U-shaped cellular manufacturing.

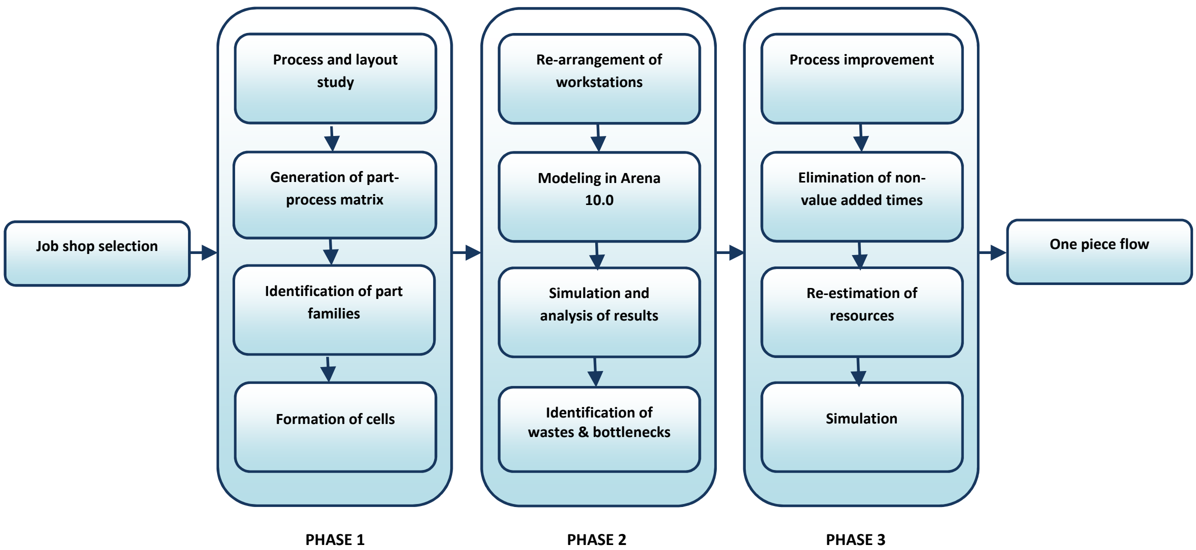

Fig. 2 Proposed methodology

5. Experimental results

We modeled and simulated our proposed and existing manufacturing systems using Arena 10.0 and we have compared these through predefined performance measures discussed in Section 3.

5.1 Work in process (WIP) inventory

Higher WIP are neither preferred nor welcomed. Lower WIP results in lower manufacturing lead times. In existing system, WIP was 22.85, but lean scheduling helped us to reduce it to 10. One Piece flow states that number of parts in process should not be more than the number of workstations. There are 10 workstations in PDO suspension rebuild job shop. We have observed that lean scheduling has provided 'One piece flow' and has comparatively reduced the WIP, making it equal to the number of workstations in the proposed system (Fig. 3).

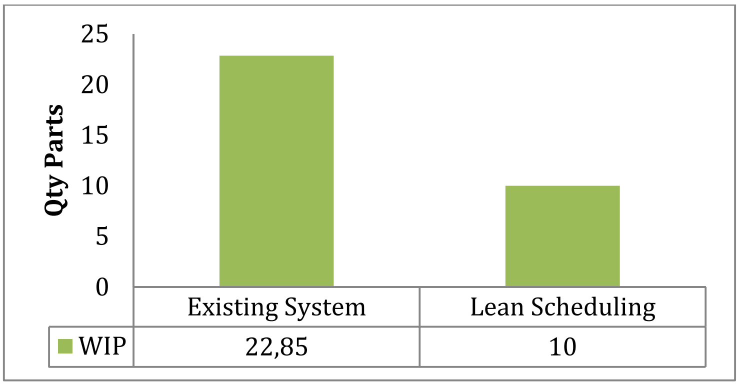

Fig. 3 WIP inventory for lean and existing system

5.2 Average cycle time

Value addition time or processing time of MLT is known as cycle time. It is time spent to convert a raw material into finished part. If we analyze the results, we can found a drastic decrease in cycle times for proposed scenario, where lean scheduling has been implemented. However, final drive and idler wheel are having almost same processing times in existing and proposed systems (Fig. 4). These parts visit few work stations as compared to others and do not undergo milling, drilling and broaching process.

Available time for production of these parts is 12000 to 12120 for 5 days, 8 hours shift. In existing system, final drive and idler wheel discs are the only parts that can be rebuilt within the stipulated time. In proposed lean scheduling, balance arm is consuming longer time than the available time. Other parts can be rebuilt within the scoped time for these parts (Table 1).

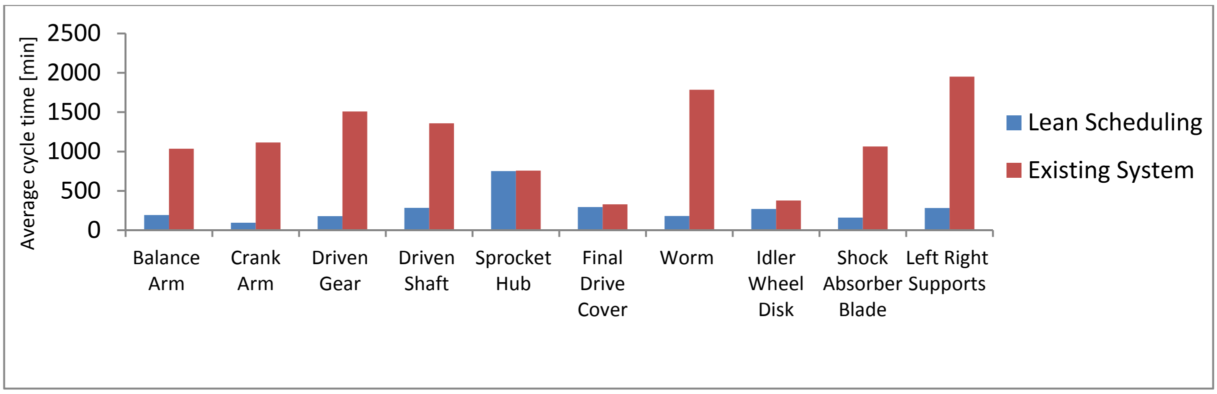

Fig. 4 Average cycle times for lean and existing system

Table 1 Average cycle times for lean and existing system

S. No.	Part	Qty	Existing system	Lean scheduling
1	Balance Arm	100	1034.8	193.24
2	Crank Arm	20	1115	97.75
3	Driven Gear	20	1507.7	178.65
4	Driven Shaft	20	1358.3	284.89
5	Sprocket Hub	20	757.7	751.11
6	Final Drive Cover	20	328.57	294.47
7	Worm	20	1785.4	181.81
8	Idler Wheel Disc	20	377.91	271.11
9	Shock Absorber	40	1065	160.76
10	Left, right Support	20	1950.9	282.3

5.3 Manufacturing lead time

Manufacturing lead times include time spent on value added and non-value-added activities. We have analyzed the existing situation with the intent to discover the effect of non-value addition on MLT. Unfortunately, the time spent on wastes is too large in comparison to the actual processing times. This scenario clearly indicates that there exists room for improvement in the existing systems and non-value addition times must be decreased to increase the productivity of the system (Fig. 5). In order to decrease these non-processing times, we implemented Kaizan, quick changeover and One Piece flow for our proposed system.

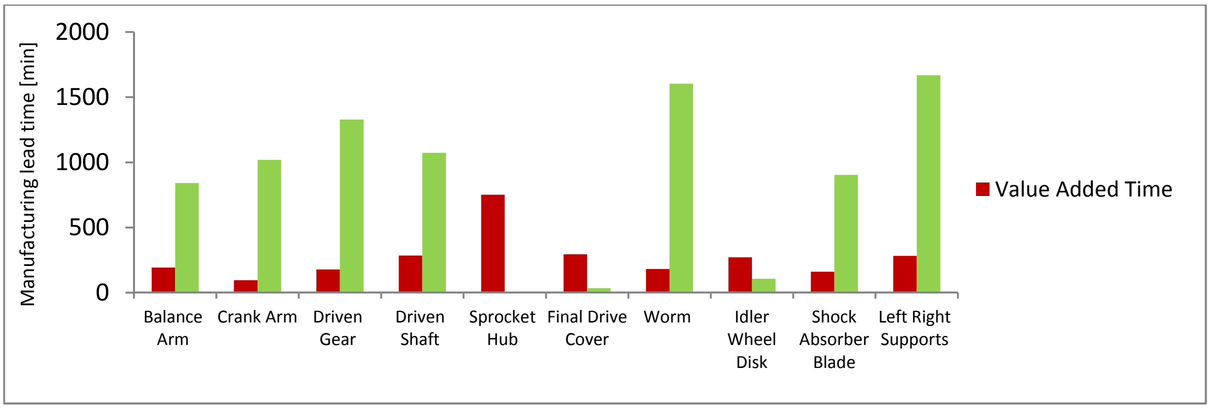

Fig. 5 MLT for lean and existing system

5.4 Lateness in delivery commitments

After analysis of the results in Fig. 6, we found that proposed system is also having lateness in production of one part, i.e. balance arms with lateness of about 4 days.

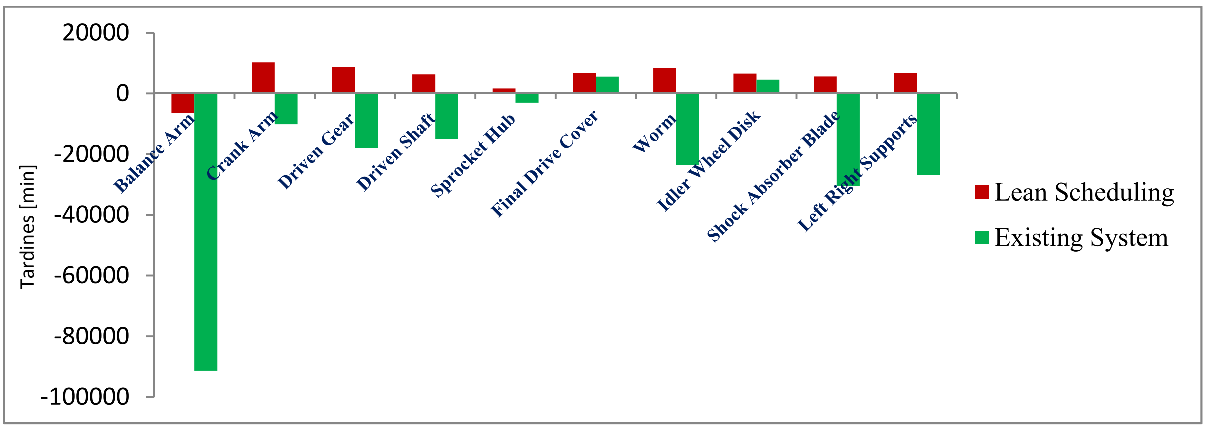

Fig. 6 Tardiness for lean and existing system

We reviewed the reasons for delay in processing of balance arms and found that these parts are being delayed due to extensive load on turning work stations and can be improved by reducing queue times at these workstations. However, existing system was facing severe tardiness and was unable to meet the production targets. Lateness in the existing system can be related with resource utilization given in section 5.7. Available time for rebuild of these suspension parts approximates from 12000 to 12120 based on 5 days, 8 hours shift. Results also reflect the need to review the planned targets for the job shop (Table 2).

Either the target of balance arms should be re-evaluated or efforts should be made to improve the process time on centre lathes for these parts. This can be done through use of tungsten carbide tooling to avoid unnecessary delays and reviewing the NC program for these parts.

Table 2 Tardiness for lean and existing system

S. No.	Part	Existing system	Lean scheduling
1	Balance arm	-91360	-7204
2	Crank arm	-10180	0
3	Driven gear	-18034	0
4	Driven shaft	-15046	0
5	Sprocket hub	-3034	0
6	Final drive cover	0	0
7	Worm	-23588	0
8	Idler wheel disc	0	0
9	Shock absorber	-30480	0
10	Left, right support	-26898	0

5.5 Throughput

We have plotted achieved throughput against monthly target for existing system and proposed lean scheduling (Fig. 7). We have again noticed that sprocket hubs and balance arms are not meeting the targeted deadlines for the proposed system. We have found that excessive queue times at turning work station are the reason for this delay and can be further improved if processing time and setup time can be reduced for these parts. These parts have higher setup times and this can be reduced through use of some specialized fixtures to accommodate speedy changeover of parts during machining. Existing system is capable to produce final drive cover and sprocket hubs in desired targeted quantity. It severely lacks in production of balance arms and left right supports (Table 3).

This job shop mostly seeks the support of sister job shops to help meet the targeted quantity. Our proposed system lacks in sprocket hubs mainly due to non-availability of broaching machine and balance arms due to heavy load on centre lathes.

Table 3 Throughput for lean and existing system

S. No.	Part	Targets	Existing system	Lean scheduling
1	Balance arm	100	12	62
2	Crank arm	20	11	20
3	Driven gear	20	8	20
4	Driven shaft	20	9	20
5	Sprocket hub	20	16	17
6	Final drive cover	20	20	20
7	Worm	20	7	20
8	Idler wheel disc	20	20	20
9	Shock absorber	40	11	40
10	Left, right support	20	6	20

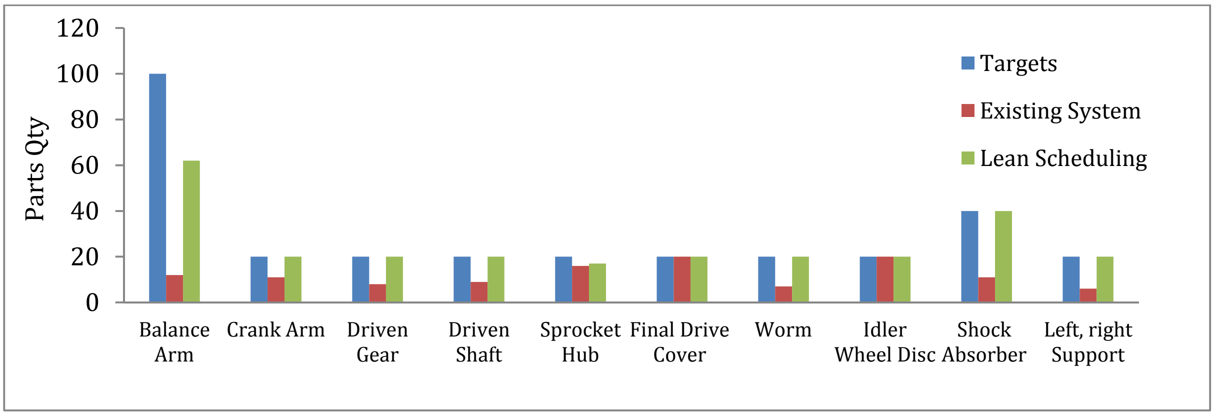

Fig. 7 Productivity for lean and existing system

5.6 Workplace utilization

Lean scheduling has been helpful to reduce the space requirement for parts waiting for processing at next stations (Fig. 8). Secondly, it has fairly reduced the work stations with provision of sophisticated work stations that are capable to perform multiple jobs. CNC milling centers can be used to replace lathes, milling, and drilling stations.

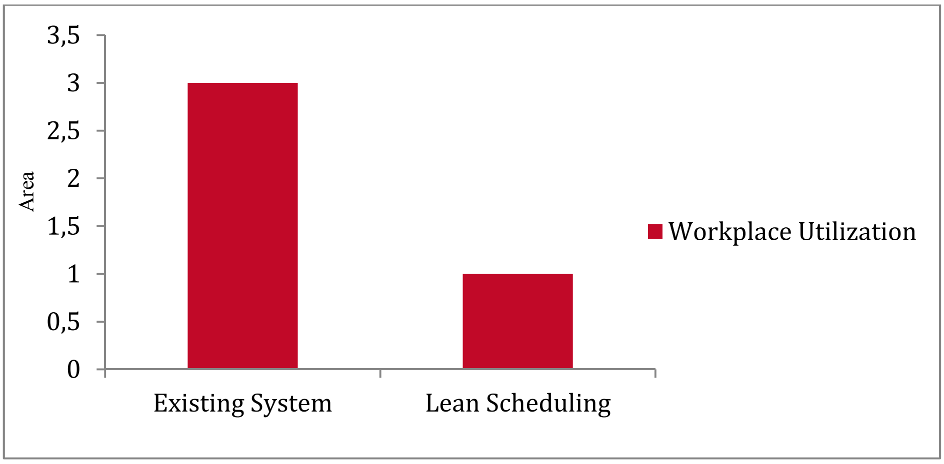

Fig. 8 Space utilization for lean and existing system

5.7 Resource utilization

Resource utilization is the ratio of available time and resource utilized time. Our research found it that most of the workstations are under-utilized. Some workstations, i.e., centre lathe and gear lathe, are causing unnecessary delays and contribute to larger waiting times for the parts in the queue. We identified improvements for these workstations. We suggested fixtures for these workstations to reduce setup times. These workstations were suffering lack of tooling for machining purpose. Secondly, there was longer time to replace the faulty parts due to lack of necessary inventory of capacitors, servo motors, belts, and gears. These improvements helped us to improve the mean time to failure and break down times. A comparative study of existing and proposed system is given in Fig. 9. We improved utilization through balancing of processing times and addressing the saurated and starving workstations.

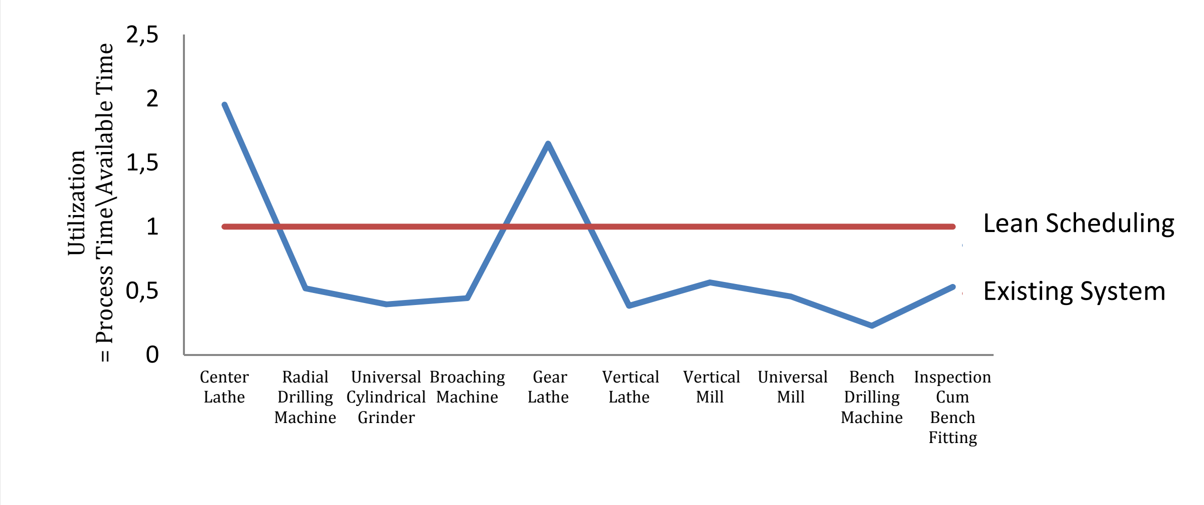

Fig. 9 Resource utilization

5.8 Cost analysis

Manufacturing cost for a product in production setup consists of fixed and variable costs. Variable costs change with the change in level of production activity. However, fixed costs remain constant and are not influenced by production activity. Manufacturing cost is mathematically represented as: *Total Cost = Fixed Cost + Variable Cost (Quantity of Parts)* [7, 16].

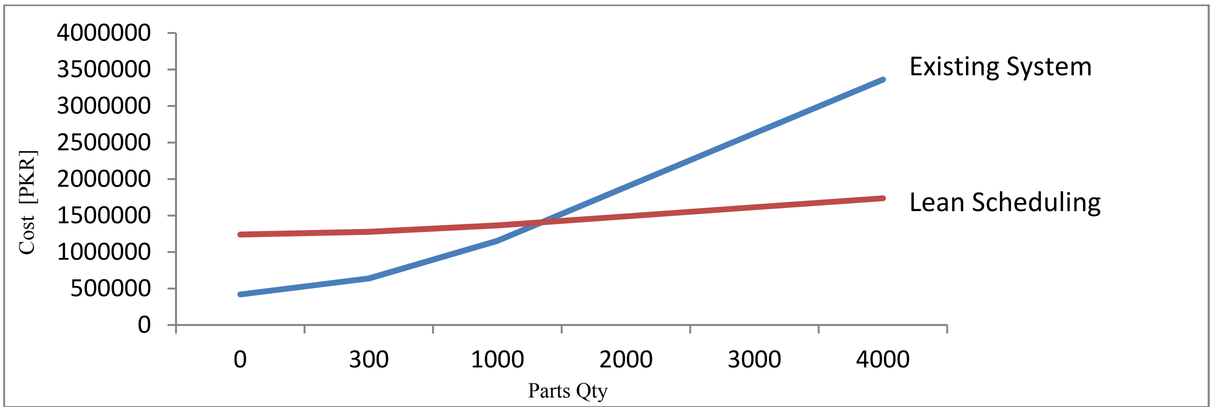

Fig. 10 Cost analysis for lean and existing system

Fixed and variable costs for existing system are 0.42 and 0.00074 Million PKR (1 US $ = 46 PKR.). Similarly, for proposed system these costs are 1.24 and 0.00015 Million PKR. We have performed the cost benefit analysis for both systems and found that proposed system will be beneficial after the production of 1500 parts (Fig. 10). PDO is producing 300 parts in one month (Fig. 11). It can be inferred from this cost analysis that lean system will be beneficial after passage of first five months.

These results showed that lean scheduling can be helpful in improvement of delivery times for job shop environment (Table 4). In problem statement, we have identified three major objectives for our study. These include on-time delivery, improved resource utilization and determination of exact production capacity of job shop. We were able to determine the exact targets for job shop. It was not possible to produce balance arms and sprocket hubs according to planned commitments within available resources. This work helped to propose suggestions for enhancement in resources to meet the targeted deliveries of balance arms and sprocket hubs.

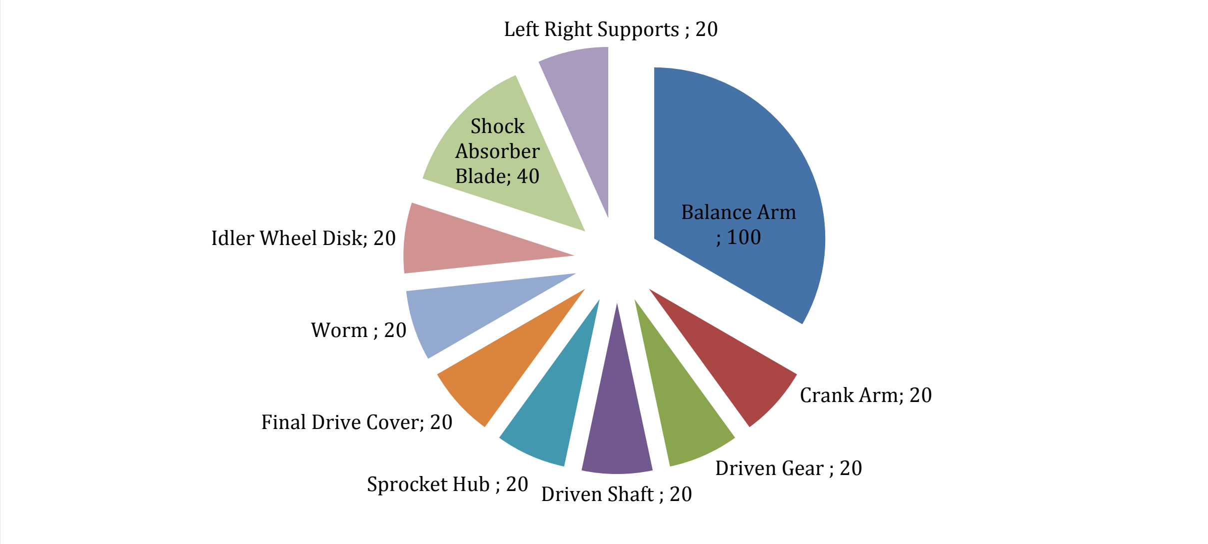

Fig. 11 Production targets of job shop

Table 4 Comparison of proposed and existing system

S. No.	Parameter	Unit	Existing system	Lean scheduling
1	WIP	no.	22.85	10
2	MLT_{avg}	Time (min)	2400.12	715.5
3	Space utilization	area	3	1
4	Cycle $time_{avg}$	Time (min)	1128.13	269.42
5	Throughput	no.	46.45	94.7
6	$Lateness_{avg}$	Time (min)	-20851	+4864.98
7	$Utilization_{avg}$	ratio	0.53	1.0

6. Conclusion and future work

Lean philosophy is preferred in manufacturing organizations due to its ability to produce the products at competitive prices. Lean scheduling is conceptually similar to lean manufacturing and revolves around elimination of wastes, continuous improvement, total preventive maintenance and quick changeover. Our implementation of lean in job shop reflected that lean scheduling is possible in job shop as well and can bring positive impact on manufacturing activity. It may be helpful to reduce the long lead times with reduction in non-processing times and implementation of 'One Piece flow'. Scalability of our proposed approach for larger setups needs validation. We have implemented our approach on one process, i.e. machining in job shop. There exists a lot of room to further expand it and implement it on the complete process flow of suspension parts. We have made few assumptions about the arrival times of the parts. Sometimes, predecessor activities may undergo delays and cannot be completed as desired. Such delays will effect our proposed approach. Another drawback of our proposed approach is requirement to alter the layout and make it feasible for cellular manufacturing. Alteration is a costly activity and organizations may not opt for it. We believed that inventory of parts to repair workstations will remain replenished all times. Last but not the least aspect of our proposed system is about the fixtures to reduce setup times on workstations. Feasibility to manufacture these fixtures needs to be validated for our proposed approach. Despite these consequences, we have been successful to provide a framework to make lean job shops. Our proposed approach has been successful to challenge the stereotype that lean is for mass production and is not feasible for smaller setups.

Our proposed approach can also be used for capacity planning of job shops and provide accurate targets for production activity. We are working on this concept to determine the production capacity of newly commissioned tool shop. Secondly, we are working on a proposal to provide ideal production layout for assembly of rebuilt parts for T-80 UD battle tanks.

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We are thankful to senior management of PDO defense organization for providing us technical manuals and resources to understand the process, layout and operations of battlefield tank's manufacturing and access to rebuild and assembly shops. We are also thankful to lab incharge of Mechanical Engineering Department of UET, Taxila in helping us to procure Arena 10.0 for experimental purpose.

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Tool selection for rough and finish CNC milling operations based on tool-path generation and machining optimisation

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A B S T R A C T

Most of CAD/CAM systems lack fully-automated process planning capabilities and depend on semi-automatic capabilities that necessitate the traditional selection of tools and cutting parameters. This paper attempts to determine proper combinations of cutting tools through the generation of tool paths and optimisation of machining parameters using an example of the CNC milling process. Several machining simulations with different combinations of tool sizes were performed using MasterCAM software. Based on these simulations, substantial variations in tool paths were observed for different tool combinations and as such the optimum tool combination could only be obtained arbitrarily. The tool paths derived from machining simulations were used to optimise machining parameters, that is, cutting speed, feed rate and depth of cut with the objective of minimising production time. In this case, an optimisation model was developed as a nonlinear programming problem and solved using extended LINGO nonlinear software. The results show that the subjectivity when selecting cutting tools can be avoided when appropriate tools are chosen alongside with the generation of a tool path within a CAD/CAM system using optimised machining parameters. As a consequence, CNC machine tools could be effectively utilised and the productivity significantly improved at shorter production time and cost.

A R T I C L E   I N F O

Keywords:
CAD/CAM
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Machining optimisation
Nonlinear programming
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1. Introduction

Numerical Control (NC) technology has mainly contributed towards the automation of manufacturing processes specifically in metal cutting processes. In NC technology, numerical data are used to control operations of machine tools, material handling systems and inspection equipment in manufacturing of different products. The control is achieved through feeding the part program into the machine control unit (MCU). The accuracy and precision of components produced on NC machine tools is less dependent on skills of the operator but on the instructions contained in the part program. Actually, a computer numerical control (CNC) machine tool is accompanied with a computer where a part program can be prepared, stored and edited. MCU reads the instructions in the part program and interprets to allow the required movement of the worktable and spindle of the machine tools.

Part programming can be done manually or with the aid of the computer. Manual part programming is time consuming, error prone and limited to simple geometry. In computer-assisted part programming, much of tedious computation tasks inherent in manual part programming are performed using high-level programming languages. Automatically Programmed Tools (APT) was one of the common languages employed to describe part geometry and specify tool motions. However, such programming systems are no longer common due to emerging of CAD/CAM systems which are more convenient in defining part geometries and specifying tool paths. A CAD/CAM system has a platform where a component can be modelled in CAD and its geometric data is accessed by a CAM system to generate tool paths achieving the requirements of NC programming. Several CAD/CAM systems are available in the market such as MasterCAM, Bob CADCAM, KELLER SYMPlus and EDGECAM.

In order to accomplish a complete NC part program for application in a CNC machine tool, process planning activities should be integrated in the CAD/CAM system. Activities of process planning includes: (1) interpretation of product design data, (2) selection of machining operations, (3) sequencing of machining operations, (4) planning of work-holding, (5) selection of machine tools, (6) selection of cutting tools, (7) determination of optimal cutting parameters, and (8) determination of product routing. However, the literature shows that many of CAD/CAM systems lack fully-automated process planning capabilities but depend on semi-automatic applications which need several inputs from the user for feature identification, tool selection and determination of optimal cutting parameters. In other words, most of decisions in process planning are done manually with the assistance of a computer [1-4]. For example, most of the available CADCAM systems often do not generate optimum toolpath in CNC machining operations [5]. As a result, a full CAD/CAM integration has not yet been achieved.

A number of researchers have worked on process planning for metal cutting operations in different details. An algorithm was developed in [6] for determining the biggest possible cutter for 2D milling operation for achieving highest production rate. The algorithm is centred on the tools ability to cover target region. For any point on a target region, there must be a permissible location for a cutter such that an area covered by a cutter is fully contained in a target region. The algorithm however did not deal with minimising production cost. The study by [7] addressed the problem of selecting a sequence of end milling cutters to machine a 2.5D pocket with the goal of incurring the minimum combined cost of tool wear and machining time. A two-dimensional contour offset approach was used to find accessible areas for various tools. The accessible areas were defined as the region within the 2D contour in that the tool can reach without gouging the boundary. The decomposition of the pocket into sub-pockets was carried out based on the accessible areas of various tools. All possible sequences can be represented as a directed graph. In the graph, the nodes represented the state of the stock after the tool named in the node has accomplished the machining operation. Upstream nodes in the graph have tools of larger diameter compared to downstream nodes. Edges were weighted with the cost of machining starting from one state of the stock to another.

The research reported in [8] described a method for determining the optimal combination of cutting tool for 3D volumes or 2D profiles. Optimal tools were selected by considering residual materials that are inaccessible to oversized cutters and the relative clearance rates of cutters that can access these regions of the selected machining features. They used machining features and set of tool diameters to calculate tool access volumes and ultimately determine residual volumes. Researchers of [9] presented a method of selecting optimal tools from a set of feasible tools, considered global residual (due to presence of neck or island) and local residue (due to smallest concave radius in the pocket). They argued that the high number of tools is associated with pockets with global residue and is less than four. It was pointed out that the key factor in determining the number of tools in the optimal combinations is the ratio of the pocket area to the local residue area. When the pocket area is much larger than the local residue area, a roughing tool must be used to remove the main area of the pocket first. Some types of uncut area can occur in pocket milling but are not related to the two categories referred to by [9]. These may be caused by using large radial depth of cut, up to the size of tool diameter. The solution around this problem can be to reduce radial depth of cut or using tool paths with compensation for uncut regions as described in [10]. The tool compensation can allow radial depth of cut up to the size of tool diameter. In another attempt to avoid uncut areas especially at corners of the part, the tool may be offset by tool radius to create the first tool path, and then the remaining tool paths can be obtained by offsetting the previous tool paths by a distance of 0.85 multiplied by the diameter of the tool [11]. Researchers in [12] developed an optimised cutting tool selection model as an input to CADCAM system to automatically machine recognised features based on ISO STEP format that enables information exchange within CADCAM software. In their work, a Rule-Based Knowledge and Decision System generates the cutter and inserts; then selects the cutting conditions from Sandvic Coromant database for each manufacturing feature.

The optimisation of tool selection proposed by [13] used Artificial Intelligence whereby tool paths were considered alongside with tool selection method. In this work, tool paths were determined within Matlab environment and the optimisation problem was solved using Genetic Algorithm. However, the effect of machining strategy was not addressed. Previous work [14] showed that Genetic Algorithm has been the most widely used optimisation procedure for various objectives including reduction of cost, tool changing time and tool travel path, and minimising machining time. Other methods are Particle Swarm optimization (PSO), Artificial Neural Networks (ANN), Ant Colony Optimization (ACO) and Artificial Immune System (AIS).

Although nowadays process planning can be achieved by using computer-aided process planning (CAPP) systems, the linkage of CAPP to CAD/CAM systems is still not well established. Much of the research work is yet to contribute into efficient commercial CAD/CAPP/CAM system with a reason that CADCAM systems (or NC generating software) still require a lot of user input especially in process planning. The optimum set of tools is specific for a particular geometry of a machining feature. Bigger tools can remove material from the work-part much faster but leave larger residual material and operate at higher production cost or time. The use of more than one tool may or may not necessarily lead to reduction in production cost or time. In such as situation, the use of optimisation procedure that is not implemented within CADCAM systems is inevitable. The major contribution of this study is based on the selection of cutting tools for CNC milling operations through tool-path generation and machining parameter optimisation. Specifically, the study is intended to create a geometric feature and perform extensive machining simulations on different sets of cutting tools to reveal the economics of CNC milling process in terms of production time.

2. Methodology

Trial machining simulations for CNC milling operations were conducted on MasterCAM system. This system is commonly used in industries and has the capability of creating part geometries as well as generating tool paths and associated NC codes. Before simulations were done on MasterCAM, a test component was selected. The selected component was a side plate of a sugar-cane crusher. This component is geometrically complex with intricate pockets and islands as shown in Fig. 1(a) and Fig 1(b).

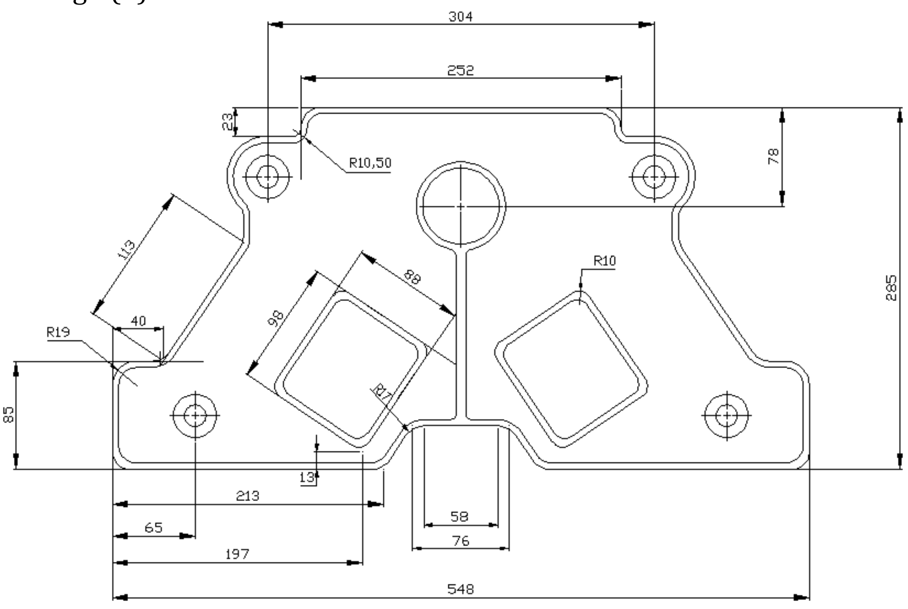

Fig. 1(a) A side plate of sugar-cane crusher in orthographic view

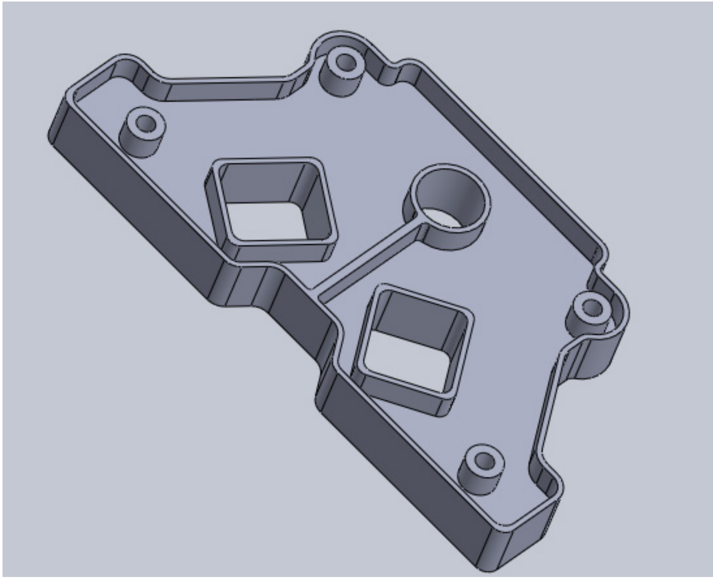

Fig. 1(b) A side plate of sugar-cane crusher in 3D view

Tool combinations were selected in such a manner that bigger sets of tools can at least gouge the pocket of the work-piece and smaller sets of tools can pass through the smaller constrictions within the pockets.

The following tool combinations were tried out: Single tools, two-tool combinations and three-tool combinations. For each simulation trial, the total length of the tool path for each tool was recorded. A radial width of cut equal to 0.85 of tool diameter was selected to avoid the existence of uncut regions. Since it is known that the length of the tool path and the corresponding machining time depends on the tool path strategy, e.g. spiral, zigzag, one way etc. [5, 15], the zigzag strategy was used throughout the machining tests. Previous works [16] shows that zigzag tool path is more favourable than any other strategy in terms of cycle time in rough machining of pockets. From simulations, it can be clearly noted whether or not there is any residual materials left on the work-piece. In order to obtain a comprehensive process plan, tool paths derived from machining simulations were used to optimise the machining parameters such as cutting speed, feed rate and depth of cut for CNC milling operations. The optimisation of machining parameters is conducted to achieve the best performance of the machine tool in terms of production time. The optimisation model for minimising production time needed for both rough and finish CNC milling operations can be formulated as follows:

$$\text{Minimise } t_p = \sum_{i=1}^{N}\left(\frac{\pi D_i L_i}{1000 v_i f_i Z_i} + \frac{\pi D_i^{1-w_T} L_i W_i^{\delta_T} Z_i^{\lambda_T - 1}}{1000 E_T} v_i^{\alpha_T - 1} f_i^{\beta_T - 1} d_i^{\gamma_T} t_r\right) \tag{1}$$

Subject to:

$$v_i^L \leq v_i \leq v_i^U, \forall i \tag{2}$$

$$f_i^L \leq f_i \leq f_i^U, \forall i \tag{3}$$

$$d_i^L \leq d_i \leq d_i^U, \forall i \tag{4}$$

$$E_F D_i^{\omega_F} v_i^{\alpha_F} f_i^{\beta_F} d_i^{\gamma_F} W_i Z_i \leq F_{max,} \forall i \tag{5}$$

$$E_P D_i^{\omega_P} v_i^{\alpha_P} f_i^{\beta_P} d_i^{\gamma_P} W_i Z_i \leq P_{max,} \forall i \tag{6}$$

Where: t_p is the production time; v_i the cutting speed; f_i the feed rate; and d_i the depth of cut. The developed model is a nonlinear programming problem containing the nonlinear objective function as well as linear and nonlinear constraints. This model can easily be solved with extended LINGO software to achieve the optimal cutting speed, feed rate and depth of cut and yet meeting the minimum production time. Various methods can also be used to solve the model including particle swarm optimisation (PSO), artificial neural networks (ANN), ant colony optimisation (ACO) and artificial immune system (AIS). The selection of LINGO software was based on the fact that it is capable of solving unlimited size of linear and nonlinear constraints and unlimited number of integer, nonlinear and global variables [17]. The first term of the objection function in Eq. 1 defines the machining time while the second term of the equation defines the tool replacement time. Constraints (2), (3), and (4) express the allowable limits of the minimum and maximum cutting speed, feed rate, and depth of cut, respectively. The cutting force and cutting power are restricted by maximum limits in constraints (5) and (6), respectively.

3. Results and discussion

Trials of machining simulations with different combinations of tool sizes were performed using MasterCAM software with the intention of selecting the optimum combinations of tool size. On conducting the simulations, a stock size was selected based on prismatic bounding box of the component with allowances of 5 mm in all the three machining axes. Tool paths were automatically generated as shown in pictorial view (Fig. 2).

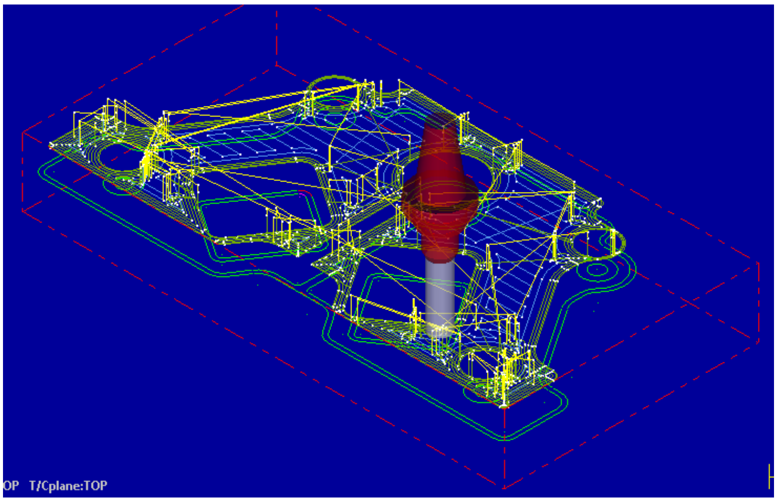

Fig. 2 Tool path generated in MasterCAM

Four single tools were tried out to generate tool paths. As shown in Table 1, the tool with a diameter D = 6 mm provides the minimum length of tool path (L = 30269 mm) without any island left in the pockets. In Table 2, seven sets of two-tool combinations were tried out in the simulation of tool path. The results show that tools with diameters of 40 mm and 5 mm in combination provide the minimum length of tool path (L = 32801 mm) without islands. Table 3 shows the simulation results for three-tool combinations whereby tools with diameters of 40 mm, 20 mm and 5 mm provide the minimum length of the tool path (L = 25873 mm) without islands. By comparison of all trial simulations with single tool, two-tool combinations and three-tool combinations, it is observed that a set of three tools with diameters of 40 mm, 20 mm and 5 mm is optimum as it provides the minimum length of tool path. However, this reason alone may not necessarily lead to the minimum production time because other machining parameters such as cutting speed, feed rate and depth of cut are not considered. In this case, further analysis is to be performed using the formulated optimisation model to determine the optimum machining parameters in order to determine the appropriate tool combination which provides the minimum production time. Additional data for the model is given in Tables 1, 2 and 3. These include number of tool teeth z; radial depth of cut W (mm); limits of machining parameters v^L (m/min), v^U (m/min), f^L (mm/tooth), f^U (mm/tooth), d^L (mm), d^U (mm). Tool life constants are given as α_T = 3.03, β_T = 1.51, γ_T = 1.51, λ_T = 0.3, δ_T = 0.3, ω_T = 1.36, E_T = 148880 whereas cutting force and power constants are given as ω_F = -0.86, α_F = 0, β_F = 0.72, γ_F = 0.86, ω_P = -0.86, α_P = 1, β_P = 0.72, γ_P = 0.86, E_F = 0.642, E_P = 0.0107, F_{max} = 0.8 kN , P_{max} = 1.5 kW [18, 19].

Table 1 Generated tool path L (mm) with a single tool

S/N	D	L	z	W	v^L	v^U	f^L	f^U	d^L	d^U
1	6	30269	2	5.1	9	30	0.063	0.127	1	4
2	5	34593	2	4.25	9	30	0.063	0.127	1	4
3	4	42788	2	3.4	9	30	0.063	0.127	1	4
4	3	57553	2	2.55	9	30	0.063	0.127	1	4

Table 2 Generated tool path L (mm) with a combination of two tools

S/N	D	L	z	W	v^L	v^U	f^L	f^U	d^L	d^U
1	40	2784	6	34	60	120	0.063	0.152	2	8
	5	30017	2	4.25	9	30	0.063	0.127	1	4
2	35	3460	6	29.75	60	120	0.063	0.152	2	8
	5	30017	2	4.25	9	30	0.063	0.127	1	4
3	30	4507	6	25.5	60	120	0.063	0.152	2	8
	5	30018	2	4.25	9	30	0.063	0.127	1	4
4	25	5360	4	21.25	60	120	0.063	0.152	2	8
	5	30017	2	4.25	9	30	0.063	0.127	1	4
5	20	6947	4	17	9	30	0.063	0.127	1	4
	5	30017	2	4.25	9	30	0.063	0.127	1	4
6	15	9877	4	12.75	9	30	0.063	0.127	1	4
	5	30018	2	4.25	9	30	0.063	0.127	1	4
7	10	14780	2	8.5	9	30	0.063	0.127	1	4
	5	30474	2	4.25	9	30	0.063	0.127	1	4

Table 3 Generated tool path L (mm) with a combination of three tools

S/N	D	L	z	W	v^L	v^U	f^L	f^U	d^L	d^U
	40	2784	6	34	60	120	0.063	0.152	2	8
1	20	10990	4	17	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4
	40	2784	6	34	60	120	0.063	0.152	2	8
2	10	20823	2	8.5	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4
	35	3460	6	29.75	60	120	0.063	0.152	2	8
3	20	10990	4	17	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4
	35	3460	6	29.75	60	120	0.063	0.152	2	8
4	10	20823	2	8.5	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4
	30	4507	6	25.5	60	120	0.063	0.152	2	8
5	10	20823	2	8.5	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4

Based on the optimisation results in Tables 4, 5 and 6, a single tool with a diameter D = 3 mm provides the minimum production time (t_p = 70.7 min) while two tools with diameters of 40 mm and 5 mm in combination provide the minimum production time (t_p = 65.4 min) and three tools with diameters of 40 mm, 20 mm and 5 mm in combination provide the minimum length of the tool path (t_p = 73.6 min).

Table 4 Tool path and machining parameters with single tool

S/N	*D*	*L*	*z*	*W*	v_{opt}	f_{opt}	d_{opt}	t_p
1	6	30269	2	5.1	30	0.127	1	76.0
2	5	34593	2	4.25	30	0.127	1	71.4
3	4	42788	2	3.4	30	0.127	1	70.7
4	3	57553	2	2.55	30	0.127	1	71.4

Table 5 Tool path and machining parameters with two tools

S/N	*D*	*L*	*Z*	*W*	v_{opt}	f_{opt}	d_{opt}	t_p
1	40	2784	6	34	120	0.152	2	65.4
	5	30017	2	4.25	30	0.127	1	
2	35	3460	6	29.75	120	0.152	2	65.8
	5	30017	2	4.25	30	0.127	1	
3	30	4507	6	25.5	120	0.152	2	66.3
	5	30018	2	4.25	30	0.127	1	
4	25	5360	4	21.25	120	0.152	2	68.4
	5	30017	2	4.25	30	0.127	1	
5	20	6947	4	17	30	0.127	1	90.6
	5	30017	2	4.25	30	0.127	1	
6	15	9877	4	12.75	30	0.127	1	92.6
	5	30018	2	4.25	30	0.127	1	
7	10	14780	2	8.5	30	0.127	1	123.9
	5	30474	2	4.25	30	0.127	1	

Table 6 Tool path and machining parameters with three tools

S/N	*D*	*L*	*Z*	*W*	v_{opt}	f_{opt}	d_{opt}	t_p
1	40	2784	6	34	120	0.157	2	73.6
	20	10990	4	17	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	
2	40	2784	6	34	120	0.157	2	114.2
	10	20823	2	8.5	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	
3	35	3460	6	29.75	120	0.157	2	74
	20	10990	4	17	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	
4	35	3460	6	29.75	120	0.157	2	114.6
	10	20823	2	8.5	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	
5	30	4507	6	25.5	120	0.157	2	115.1
	10	20823	2	8.5	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	

By comparison of tool paths and machining parameters for single tool, two-tool combinations and three-tool combinations, it is observed that a set of two tools with diameters of 40 mm and 5 mm is optimum as it provides the minimum production time (t_p = 65.4 min). As noted, this observation is different from the previous findings where a set of three tools with diameters of 40 mm, 20 mm and 5 mm provided the minimum length of the tool path (L = 25873 mm), but without considering other variables such as machining parameters.

The set of two tools providing the minimum production time can be operated efficiently using the following machining parameters: v_{opt} = 120 m/min, f_{opt} = 0.152 mm/tooth, d_{opt} = 2 mm for 40 mm tool in rough milling operation; and v_{opt} = 30 m/min, f_{opt} = 0.127 mm/tooth, d_{opt} = 1 mm for 5 mm tool in finish milling operation. The consideration of two selected tools and efficient machining parameters in milling operations is reasonable for application to the manufacturing shop floor. This fact is supported by the work of [9] which concluded that for pockets with global residuals, the optimum number of tool combination is less than four while for pockets with local residuals the optimum number of tools may be one or two.

4. Conclusion

The main function of CAD/CAM systems such as MasterCAM is to integrate the design and manufacturing activities using computer technology by creating geometric features and generating automatic NC codes for application on CNC machining operations in one platform. However, the selection of cutting tools and optimisation of machining parameters is difficult to achieve in CAD/CAM systems due to their limitation to fully automate the process planning. In reality, some of the process-planning activities are not linked into CAD/CAM systems. This paper has come up with a method whereby the selection of cutting tools for CNC milling operations is done using the generated tool path and the optimised machining parameters. In this manner, the arbitrary choice of tools can be avoided and the performance of the machine tool can be improved. Several trials of machining simulations with different combinations of tool sizes were performed using MasterCAM software. The results have shown that there are substantial variations on tool paths for different tool combinations, and a subjective way of obtaining the optimum tool combination can be avoided by optimising the cutting conditions to achieve time or cost effective production of parts. This approach is a step towards automating process planning in CADCAM systems. Its main advantage is that the optimum selection of tools can be achieved using already existing algorithms and software tools. However, interfacing different software modules may pose a major drawback and hence the need for future research.

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The impact of technical and organisational innovation concepts on product characteristics

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A B S T R A C T

The main objective of this paper is to determine the adoption of technologies and organisational concepts in production companies and to analyse how selected technical and organisational concepts affect products' characteristics and their introduction onto the market. A further purpose of this paper is to analyse the impact of technical and organisational concepts on the product complexity and to identify where most impulses for innovation come from, as well as their impact on the product complexity. The results are based on a sample of 89 Slovenian manufacturing companies, the data being obtained through the 2012/13 European Manufacturing Survey edition, providing information on the use and upgrading of the more used technologies and organisational concepts. We found that high usages of technical and organisational concepts have a positive impact on the product characteristics in terms of increasing the proportion of complex products. The results also showed that companies obtained more internal information about new products via sales departments whilst the customers were still the important external source of innovation.

A R T I C L E   I N F O

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1. Introduction

Fierce competition, harsh economic conditions in the domestic and international environment are becoming constants for business [1]. With rapid changes in technology, and global competition, the success of many organisations has become progressively more dependent on their ability to bring innovative products to the market [2]. Therefore, companies have to constantly explore, invent, innovate and create a new value, which will ensure the existence and further development of the company [3]. The introduction of new management practices is an important issue for companies as they seek to upgrade their productivity, improve the quality of the supply and retain competitiveness [4]. Most commonly innovations are associated with research and development (R&D) activities of the products. Numerous studies prove that increasing investment in R&D activities leads to innovative products, which enables companies to achieve competitive advantages and achieve greater market shares [5]. Non-technical innovation, which includes organisational (or management) and marketing innovation, are an emerging approach, as they were not recognized as innovations until the third edition of the Oslo Manual [6]. According to Camisón and Villar-López, organisational innovations (OI) currently represent one of the most important and sustainable sources of competitive advantages for businesses, but they have not been sufficiently studied, nor has been their impact on innovation and financial effects [7]. Keupp et al. made an extensive literature review on innovation management, analysing more than 342 articles. They found out that there is a low number of papers dealing with the field of OI, while the number of papers in the field of product (technical) innovation (TI) is very high [8]. Nevertheless, there are studies confirming positive effects of OI (Camisón and Villar-López, 2011; Rosenbusch et al., 2011; Bradley et al. 2012; Laforet 2011) as well as how to identify and measure OI in enterprises (Armbruster et al., 2008) [5, 6, 9-11].

The main objective of this paper is to determine the degree of use of TI and OI concepts in production companies and to analyse how chosen TI and OI concepts affect the product characteristic and their introduction on the market. Furthermore, we wish to identify where the most impulses for innovation are coming from and their impact on the product complexity. We also want to analyse the impact of TI and OI concepts on the product complexity. The structure of the remainder of the paper is as follows. Section 2 includes a review of relevant literature. Section 3 describes used research methodology. Section 4 comprises the results of the analysis and discussion while the conclusions are presented in Section 5.

2. Literature review

Chiva and Alegre claim that due to increasing competition, innovations are rapidly becoming a key factor for the success and survival of businesses [12]. Camisón and Villar-López argue that majority of researches on innovation types has followed a technical view [7]. Armbruster et al. claim that non-technical innovations are having an increasingly important role in a better understanding of innovation and its impact on the competitiveness of enterprises, however they emphasize that the existing literature on OI is diversed and dispersed or does not yet exist [5, 13]. Prester argue that OI are a multidisciplinary area of research, that they are a dynamic and iterative process of creating, developing, and producing products, services, processes or policies that are new to the organisation [14]. Lam claims that there is still no consensus on a definition of the term OI [15]. Damanpour and Aravind have undertaken a major study in which they determined the OI as the use of new management and business concepts and practices and showed the overlap of administrative, organisational and managerial innovations [16]. However, Camisón and Villar-López advocate the OECD definition, which defines the OI as the implementation of a new organisational method in the company's business practices, workplace organisation or external relations. The distinguishing features of OI compared to other organisational changes in a company, is the implementation of an organisational method (in business practices, workplace organisation or external relations) that has not been used before in the company and it is the result of strategic decisions taken by management. OI have a tendency to increase company performance by reducing administrative and transaction costs, improving work-place satisfaction (and thus labour productivity), gaining access to non-tradable assets (such as non-codified external knowledge) or reducing costs of supplies. Examples would be the introduction of practices for codifying knowledge by establishing databases of best practices, lessons learnt and other knowledge, so that they are more easily accessible to others: the introduction of training programs for employee development and improved employee retention or the initiation of a supplier development program [17].

Hong, Oxley and McCann, who have studied how our understanding of innovation developed over the past few decades say, that the understanding of innovation and the role of innovation in business systems, greatly evolved over the years. Today, innovation is regarded as a multidimensional issue that can be addressed in several contexts, as sources of innovation can have a crucial impact on the competitiveness of participants in the industry [18]. Although De Faria and Mendonca in a paper on the topic of innovation conclude that a direct and unequivocal link between the growth of the company, its effectiveness and its innovative activity is still very difficult to prove [19], there are several studies proving that adoption of concrete organisational concepts has a remarkable impact on the ability of enterprises to improve their performance. Camisón and Villar-López proved that OI have a positive effect on the competitive advantage of companies and thus on financial performance [7]. Jiménez-Jiménez and Sanz-Valle proved that organisational learning, which falls into domain of Human resources management, does in fact lead to greater innovation and business performance [20]. Mol and Birkinshaw found out that management innovation (another term for OI) is positively associated with company performance in the form of subsequent productivity growth [4]. Laforet conducted the study in order to examine organisational innovation in small and medium-sized enterprises in the district of Sheffield, England. She focused on three types of organisational innovation namely new product development, process innovation and a new way of working. Positive results from the introduction of organisational innovations are reflected as an increase of reputation and corporate image, increase of operational efficiency and reduction of operating costs, an employment of a more educated workforce [21].

The current literature does not specify which OI contribute to which source of competitiveness and measurement in the field of competition, it is also quite a bit of literature. Jin et al. say that only a few studies thoroughly examine the relationship between the types of innovation and business performance of enterprises, especially in the field of OI [22]. Crossan and Apaydin in paper on OI on the basis of a comprehensive meta-analysis concluded that the papers on the topic of OI are narrowly focused. According to them, narrowly focused research otherwise deepens understanding of the different facets, but on the other hand impedes the consolidation of the entire field. Breakdown of innovative activities in the literature shows that only 3 % of papers are dealing with organisational and administrative innovation [23]. A study by Evangelista and Vezzani shows that introduction of some type of organisational change tends to attach more importance (compared to the other companies) to objectives such as the reduction of the time needed to respond to customer or supplier needs and of improvement of the quality of goods or services while no association is found with the objective of reducing the cost for unit of output. The study tested the correlation between sources of innovation but not the links between sources of innovation and competitiveness of enterprises [24]. Gumusluoğlu and Ilsev have investigated the impact of the transformation of company management on OI and tries to determine whether external and internal support for innovation, as an influential factor, have impact on OI. The results showed that the transformation of the company management has a positive impact on OI within the company. This applies especially to micro and small enterprises [25]. Gunday et al. argue that researchers neglect organisational and/or marketing innovations, which in their opinion are also essential for growth and efficient operation of enterprises. Therefore, they studied the effects of innovation impacts on business by examining the technical, process, marketing and organisational innovations, where the company's success was measured in terms of innovative performance, production efficiency, market performance and financial performance [26]. Lin and Chen investigated the link between innovation, organisational effectiveness and performance in small and medium-sized manufacturing and service enterprises. The results of empirical studies have shown that the administrative innovation, rather than technical ones, are the most important factor in selling products on the market [27].

The question that arises by itself is how to measure innovation. That is also one of the main reasons why the OI are neglected by researchers since the success of the innovation process is rather difficult to measure. Several authors argue that the measurements of the efficiency of innovating are difficult to measure since the widely used innovation performance measures were conceptualized for new product development [28-32]. Evangelista et al. conducted a study measuring innovation in European industry in a way that they have pursued the proportion of newly introduced products on the market, share of development of the new product, depending on the size of companies and sector that companies operate, and the proportion of expenditure devoted to innovation [33]. Based on the research of papers, Hong, Oxley and McCannin argue that currently are in use two types of measurements, namely direct and indirect measurement. Indirect measurement is determined by measuring approximations of indicators in R&D research and patent base, which is reflection of the successfully introduced new innovative products on the market. For the economic analysis more important is direct measurement of innovation, which are objective or subjective. If a result of the measurement is indicated by summarization of numbers of innovations in new product / process, then such a measurement is considered as an objective. This form of measurement is bias because it excludes radical innovation of products that are contrary to the primary processes of innovation repeatedly unsuccessful; measurements automatically excludes unsuccessful innovations [18]. On the other hand, Belderbos argues that one way to address process innovations could be to employ productivity measures that are closely related to process innovations but underrepresented as dependent variables [28]. Armbruster et al. however argue, that with the use of definition based on a Damanpour and Evan research, it is possible to measure not only whether companies have changed their organisation (structure and processes) within a defined time period, but also to analyse ratios of adopted concrete organisational concepts in different companies and company types (sector, company size, etc.) and the extent of use within one company [5]. According to Camisón and Villar-López organisational innovation represent one of the most important sources of competitive advantage of companies, but on the other hand, there is a very limited evidence on predisposition to innovate and very few papers on organisational innovations. Therefore, in this work we concentrate on organisational innovations and their impact on innovation, and contribute to theory by researching this under investigated field.

3. Methodology

Presented data on technical and organisational issues in Slovenian manufacturing companies is a result of European Manufacturing Survey (EMS). The coordinator of the project is the Fraunhofer Institute, Karlsruhe, Germany. The research was first conducted in 1993. The first survey of manufacturing activities in Slovenia was carried out in 2004. It was repeated it in years 2006-07, 2009-10 and 2012-13. The target group are the companies from manufacturing sector with more than 20 employees. The questionnaire has 20 sections and it is eight pages long. It covers future competitive priorities of the company, the use of organisational and technological concepts, characteristics of the production process and the characteristics of the company's core product. It also covers human resource issues, and innovation issues measured in terms of generated profits by incrementally new products and radically new products (description is in accordance to OSLO Manual, 2005). The last version of questionnaire was thoroughly upgraded as we added several important topics, especially in the field of energy and material efficiency, product related services, and the use of project-oriented work in companies. We have also expanded the field of research and covered companies classified in NACE 13-15, 22-28, 30 and 32 codes (version 2).

The study included 19 TI concepts and 22 OI concepts. TI concepts were divided into 5 groups: robotics and automations (4 concepts), process and manufacturing technology (4), digital factory/IT connectivity (5), efficient use of energy and resources (4) and technologies for generating renewable energy sources (2). OI concepts were divided into 4 groups: the organisation of production (6), the organisation of work (5), standardization and conformity assessment (6), and human resource management (5). We asked companies to reveal information about upgrading already introduced concepts and the level of use (high, medium, low). For further analysis we selected TI used in at least 15 % of companies and OI concepts used in at least of 30 % of companies.

Field of new products in the survey questionnaire dealt with two issues. The first was asking if the company has launched a significantly improved new product in last three years or has it launched a radically new product in last three years – a product that is new also to the market. In both cases, the additional question was raised on a share of revenues generated by these new products.

Product characteristics or a group of company's key products were divided into four groups: product development (4 properties), manufacturing (4), the batch size (3) and the complexity of the product (3).

We asked the companies where the impulses for innovations are coming from. For internal and external resources we have included 3 areas of innovation (new products, new technical production processes and new organisational concepts).

In 2012 we sent 791 questionnaires and received 89 responses, representing 11.25 % response. If we look at companies who have returned a completed questionnaire in 2012, among them 29.2 % small, 44.9 % medium-sized and 25.8 % large companies. The results of the survey will be presented with descriptive statistics.

4. Results and discussion

First, using the frequency analysis, we are going to present the level of use and the upgrade of specific TI and IO concepts in Slovenian manufacturing companies. Our research included 19 TI concepts and 22 OI concepts. We asked companies whether they use specific innovation concept and if they upgraded it in past three years. Table 1 presents the level of use of TI concepts and their upgrade in Slovenian manufacturing companies. As we can see the most widely used TI concept are industrial robots which are used in more than half of manufacturing companies (share of 55.06 %). Other technologies are present in less than half of manufacturing companies.

On average, the highest technology use frequency is found in information and communication technologies, so called ICT support for the production processes. The most widely concept used in this group is computer exchange of information on time schedules with suppliers and customers. This concept is used in nearly half of manufacturing companies included in the survey (49.4 %). We also observed that more than a third of Slovenian manufacturing companies use software that enables the simulation of product development and production process (36 %). Slovenian manufacturing companies are increasingly realizing the importance of efficient management of resources and energy. The analysis shows that around a quarter of companies use the technology of efficient use of energy and resources, especially are forefront technologies for recapitulation of kinetic energy and process technologies to generate power. Lower on the table are companies that use nanotechnology manufacturing process or and production of micro-mechanical components and technologies in the field of nanotechnology (with less than 5 % share of use). At the bottom are companies that use technology for the production of micro-mechanical components (1.1 % share of use).

Table 1 Use of technical innovation

Technology	Share [%]	Rang	Share of upgrades [%]
Robots and automation systems			
industrial robots	55.1	1	71.4
automated warehouse management	16.9	9	60.0
collaborative robots (man-machine)	7.9	15	
intuitive software methods	4.5	16	
Process and manufacturing technologies			
technology for the processing of alloys	15.7	10	64.3
technology for the processing of composites	3.4	18	
technology for the manufacture of micro mechanical components	1.1	19	
production processes in nanotechnology	4.5	17	
Digital factory / IT connection			
computer data exchange with suppliers	49.4	2	61.4
virtual reality in production	21.3	8	52.6
virtual reality in product design	36.0	3	65.6
PLM	13.5	13	
IT systems for management ideas	25.8	5	65.5
Efficient use of energy and resources			
dry manufacture	14.6	11	
control systems to stop at light load	22.5	6	55.0
recapitulation of kinetic and process energy	31.5	4	32.1
dual- and three-generation	9.0	14	
The effectiveness of generating renewable energy			
technology for generating power	22.5	7	45.0
technologies for generating heat	14.6	12	

In terms of upgrading the TI concepts since 2009, we took into account that the use of each TI concept must be at least 15 %. This means that we excluded from further analysis those concepts that are used in less than 15 % of companies. The analysis showed that on average more than 50 % of companies upgraded previously installed technologies in their production in the last three years (from 2009 until 2012). The biggest share of upgrading can be seen in the field of industrial robots (71.4 %), followed by virtual reality in product design and management of ideas (65.6 %). Technologies for energy efficiency and technologies for generating renewable energy were upgraded in less than 50 % of cases. These technologies require higher financial investments and are quite young, therefore a lower share of upgrading is not surprising.

Share of OI concepts use in Slovenian manufacturing companies is presented in Table 2. As we can see among the top 10 most frequently used OI concepts all five concepts from the group "work organisation" are ranked among them and only one concept from the group "standardization and assessment" is in top 10 (use of quality standard ISO 9000). Teamwork in production and assembly is considered as the most widespread method of organising work, since more than 78 % of Slovenian manufacturing companies are using it. Teamwork is followed by the quality management ISO 9001 concept, present in more than 77 % of the companies. The same applies to the standardization of manual work in production. There are two more OI concepts that are represented in more than half of Slovenian manufacturing companies, namely the 5S concept (52.81 %) from the group "work organisation" and training to enhance creativity (52.81 %) from the group "management of human resources". The other OI concepts are implemented in less than 50 % of Slovenian manufacturing companies.

We have asked the companies, which OI concepts are they planning to implement in their systems in the period from 2012 until 2015. Most companies (10.1 %) plan to introduce TQM (total quality assurance methods) by 2015. This is followed by a program of staff development (9 %), while share of use of other OI concepts is below 6 %. It is obvious that the implementation of any OI is a very complex project, therefore the share of companies that are planning to introduce any of the proposed OI concepts is very low. It is also a fact that none of the proposed OI concepts is applicable to all companies (size, production type).

Fig. 1 depicts the level of use of the 10 most used technologies. Companies estimated the degree of use as low (first contact with the concept), medium (partial use of the concept) and high use (full application of the concept, for OI concepts at least 70 % of employees involved). If we classify technologies according to the share of high use, we can observe that the order of technologies is quite different. Process technologies for the processing of alloys and technologies for generating power have been, according to the use frequency, on the 10th and 7th place, but they are the in top two places among companies in terms of high utilisation of their potential.

Table 2 Use of organisational innovation

Organizational concepts	Share [%]	Rang	Share of use till 2015 [%]
Organization of production			
value stream mapping	13.5	19	10.1
customer-oriented cell / line	28.1	11	3.4
zero stock principle	27.0	12	7.9
SMED	19.1	14	4.5
TPM	49.4	6	5.6
TQM	40.4	8	10.1
Organization of work			
5S	52.8	4	5.6
standardized work instructions	77.5	2	3.4
integration tasks	40.4	8	3.4
methods for continuous improvement of processes	43.8	7	3.4
teamwork in production and assembly	78.7	1	2.2
Standardisation and assessment			
visual display of the process and status of equipment	25.8	13	4.5
ISO 9000 and other	77.5	2	4.5
6 Sigma	14.6	18	6.7
ISO 14001	16.9	17	9.0
ISO 50001: 2011	2.2	21	6.7
TCO	5.6	20	7.9
Management of human resources			
formalized workshops to generate ideas	34.8	11	4.5
instruments for retention of knowledge in the enterprise	18.0	15	9.0
part-time dedicated to creativity	18.0	15	5.6
program of staff development	39.3	10	9.0
training to enhance creativity	52.8	4	5.6

Share of high use for all other technologies is below 50 %. At the bottom of the table with 5.3 % is the technology of virtual reality in production. The prevailing opinion of companies is that they use technologies not to their full potential (medium level of use).

Fig. 2 shows the level of use of the ten most widely used OI concepts. The analysis shows that only ISO 9000 concept is highly used in more than 50 % of the manufacturing companies. Only one tenth of the companies considered use of ISO 9000 concept as low. The share of all other highly used concepts in companies is less than 50 %. The lowest shares of the highly used concepts are linked to the management of human resources (staff development programs 22.9 % and training of employees 12.8 %), which is quite concerning.

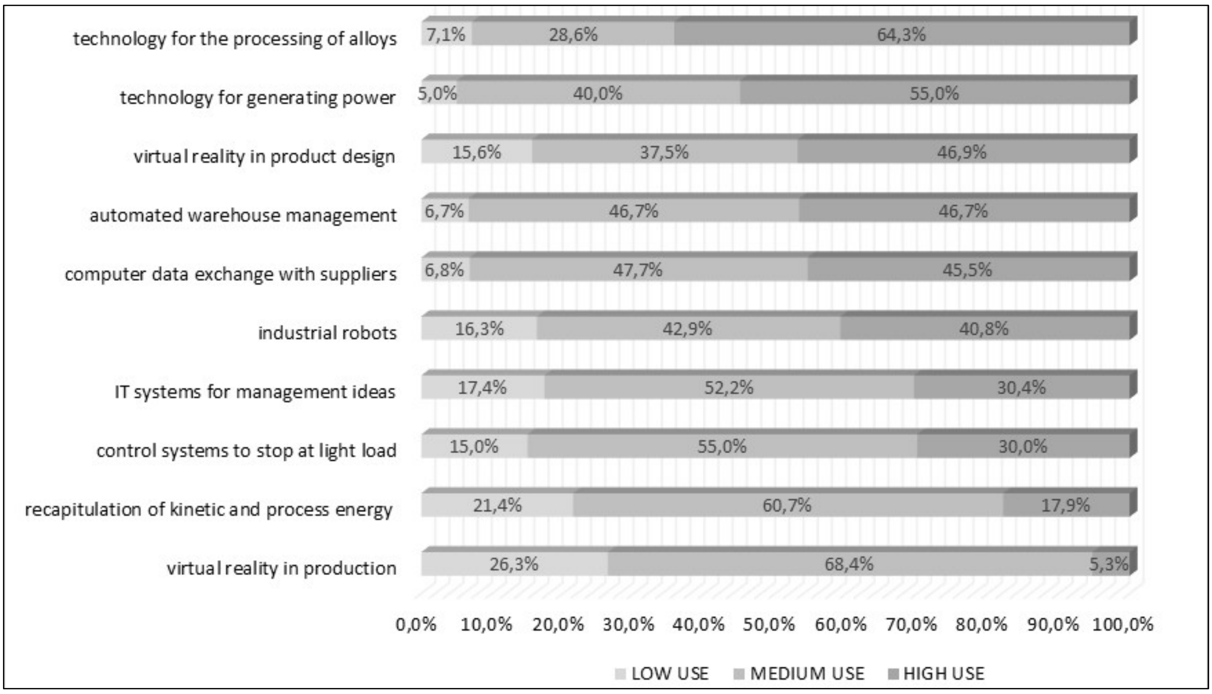

Fig. 1 Rate of use of the ten most commonly used technologies

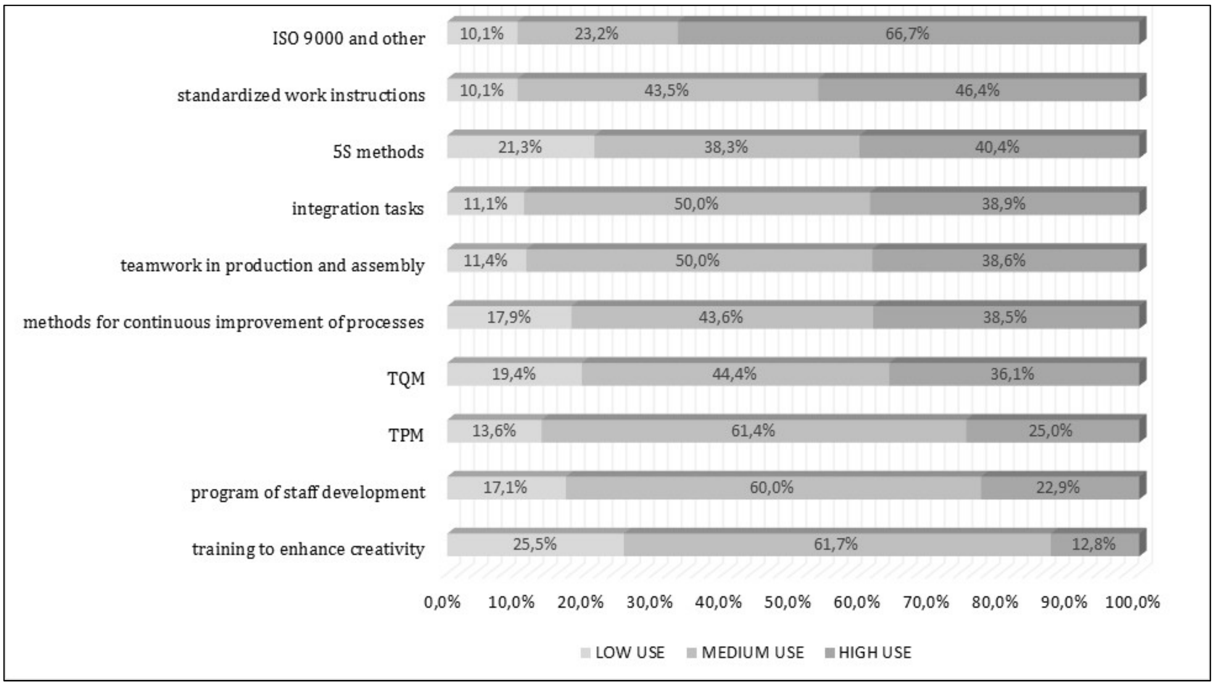

Fig. 2 Rate of use of the ten most commonly used organisational concepts

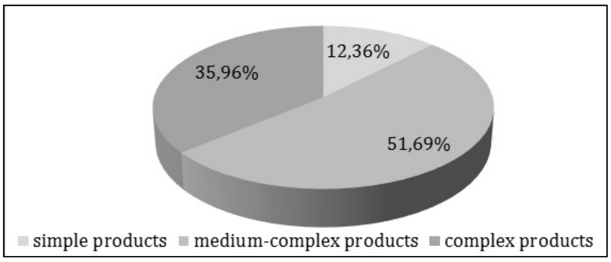

Fig. 3 Product characteristic

Fig. 3 shows product's characteristics manufactured by Slovenian manufacturing companies in terms of product complexity. This estimation is a bit subjective, but shows relatively real situation. The results of the analysis of the product complexity show that majority of companies (around 52 %) manufactures medium-complex products (e.g., pumps, several parts and technologies used, simple assembly). A little over a third of companies (35.96 %) produces complex products (machines or manufacturing systems). The remaining companies produce simple products.

Table 3 depicts impact of the number of introduced TI and OI on the complexity of the products. Companies are divided based on the number of used TI and OI concepts. Besides product complexity we have also included production type (make-to-order, assembly-to-order, make-to-stock). The results depict that more than half of the companies have introduced 1-3 proposed TI concepts, 31 % of companies have introduced 4-6 TI concepts, share of companies that have introduced 7 or more TI is around 18 %. We can observe that by increasing the number of introduced TI concepts the share of simple products is decreasing, while the share of complex products is increasing. Companies that have introduced more than 7 TI concepts no longer produce simple products. In those companies the share of complex products increased to almost 50 %. The results show that regardless of the number of TI concepts introduced, the prevailing product complexity type is medium-complex product (always share above 50 %). The prevailing production type is make-to-order production, and that is the only production type for companies with more than 9 TI concepts implemented. Another very important observation is that with the increase of installed technologies the share of companies that have introduced new product to the market in the past three years also increases.

We can see a slightly different picture when we look at the results of introduced OI concepts (Table 4). Less than a half of companies have introduced at least 6 OI concepts, around two thirds of the companies uses up to 9 OI concepts. The distribution of OI concepts used is quite equal in all five groups based on the number of OI concepts used. We can see that by increasing the number of introduced OI concepts, share of simple products is again decreasing, while by increasing the number of OI concepts used the share of complex products is increasing. In companies that use up to 9 OI concepts the share of complex products is around 30 %, the share of complex products in companies that use more than 9 OI concepts rises over 40 %. Production type does not depend on the number of OI used, especially considering the most frequent make-to-order production type. In general we can make very similar observation as with TI concepts: more OI concepts implemented increases the share of companies that have introduced new product to the market in the past three years.

Table 3 Product characteristic depending on the number of TI

Product characteristic					Type of production			
No. of TI	Share of companies [%]	Simple [%]	Medium complex [%]	Complex [%]	Make to order [%]	Assembly to order [%]	Make to stock [%]	Share of new products [%]
n=1-3	50.7	18.4	55.3	26.3	76.3	15.8	7.9	52.6
n=4-6	31.0	4.2	58.3	37.5	75.0	25.0	0.0	75.0
n=7-9	9.3	0.0	57.1	42.9	57.1	14.3	28.6	71.4
n=10-12	6.3	0.0	50.0	50.0	100.0	0.0	0.0	100.0
n ≥ 13	2.7	0.0	100.0	0.0	100.0	0.0	0.0	100.0

Table 4 Product characteristic depending on the number of OI

Product characteristic					Type of production			
No. of OI	Share of companies [%]	Simple [%]	Medium complex [%]	Complex [%]	Make to order [%]	Assembly to order [%]	Make to stock [%]	Share of new products [%]
n=1-3	20.7	27.8	38.9	33.3	83.3	11.1	5.6	55.6
n=4-6	24.1	19.0	52.4	28.6	81.0	14.3	4.8	38.1
n=7-9	23.0	10.0	60.0	30.0	70.0	25.0	5.0	65.0
n=10-12	18.4	0.0	56.3	43.8	81.3	18.8	0.0	81.3
n ≥ 13	13.8	0.0	58.3	41.7	83.3	0.0	16.7	78.6

Table 5 shows the product characteristics in terms of complexity based on the use of selected technologies. We selected 10 technologies with the highest frequency of use (see Table 1). Companies who use any of these 10 technologies have lower share of simple products manufactured comparing to average share of simple products in all analysed companies (12.36 %). On the other hand the share of medium-complex products increased for all 10 of the analysed technologies and companies that use them (51.69 %). Industrial robots have the highest share of use in companies. It was interesting to find out that the share of complex products in companies with industrial robots installed is quite below average, meaning that industrial robots are mostly used to manufacture medium-complex products. IT systems for management of ideas is a technology installed in companies that do not manufacture simple products and where the share of complex products is the highest (almost 50 %).

Table 5 Product characteristic in relation to the level of use of the 10 most used technologies

			Products		
No.	Top 10 technologies	Share of use in companies [%]	Simple [%]	Medium complex [%]	Complex [%]
1	industrial robots	55.1	10.2	63.3	26.5
2	computer data exchange with suppliers	49.9	9.1	56.8	34.1
3	virtual reality in product design	36.0	3.1	62.5	34.4
4	recapitulation of kinetic and process	31.5	5.0	65.0	30.0
5	IT systems for management ideas	25.8	0.0	52.2	47.8
6	technology for generating power	22.5	5.0	65.0	30.0
7	control systems to stop at light load	22.5	5.0	65.0	30.0
8	virtual reality in production	21.3	5.3	57.9	36.8
9	automated warehouse management	16.9	0.0	60.0	40.0
10	technology for the processing of alloys	15.7	0.0	71.4	28.6

We also analysed if high use of technology affects product complexity. If we compare product characteristics according to the share of the general use of TI concepts and share of high use of 10 most frequently used technologies, we can see that the average share of simple products with a high use of technologies increased by 3.9 %, the share of medium-complex products fell by 6.8 % the share of complex products increased by 2.9 % (Table 6).

Table 6 Product characteristic in relation to the high level of use of the 10 most used technologies

			Products		
No.	Top 10 technologies	Share of high use [%]	Simple [%]	Medium complex [%]	Complex [%]
1	technology for the processing of alloys	64.3	0.0	66.7	33.3
2	technology for generating power	55.0	9.0	45.5	45.5
3	virtual reality in product design	46.9	6.7	40.0	53.3
4	automated warehouse management	46.7	0.0	33.3	66.7
5	computer data exchange with suppliers	45.5	10.5	57.9	31.6
6	industrial robots	40.8	5.0	65.0	30.0
7	IT systems for management ideas	30.4	0.0	42.9	57.1
8	control systems to stop at light load	30.0	16.7	33.3	50.0
9	recapitulation of kinetic and process	17.9	33.3	66.7	0.0
10	virtual reality in production	5.3	0.0	100.0	0.0

We have to point out that this data can be a bit misleading as the sample of companies for some technologies becomes quite low. Therefore, we are commenting some of the technologies separately. High use of mostly widely used technologies (industrial robots and computer data exchange with suppliers) does not change the distribution of product complexity. It is different for the third most widely used technology – virtual reality in product design – where with the high use of this software the share of complex products increases to over 50 % of companies. This might lead to conclusion that the companies that use computer software for product design to its full potential are more capable to design and manufacture complex.

Similarly, we analysed the products complexity in 10 most widely used OI concepts. Table 7 shows the product characteristics based on the share of overall use of selected OI concepts. We can see that the average share of complex products has increased to 41.5 %, the share of medium-complex products is still around 51 %, while the share of simple products decreased to 7 %.

With all ten selected OI concepts the share of complex products is higher than average - 36 %. This could mean that the companies that have implemented proposed OI concepts are more prepared and capable to manufacture complex products. On the other hand investing in new OI concepts could also mean that these manufacturing companies are trying to exclude manufacturing of simple products and focus more on products with higher value added.

If the OI concepts are classified according to the share of high use, we can observe that the order of concepts has been mixed up (Table 8). If we compare product complexity according to the share of general use of OI and share of high use of the 10 most used OI, we can see that the average share of simple products with the high share of use of OI has decreased by 3.4 %, the share of medium-complex products has decreased by 6.2 %, while the share of complex products increased by 9.5 %. Based on that we can conclude that the high use of selected OI concepts has even stronger impact on the ability for companies to manufacture complex products. Looking at specific OI concepts we can point out several things. OI concepts program of staff development and training to enhance creativity have the lowest share of high use, but on the other hand, we can see that the share of complex products in companies with the high use of these two OI concepts is extremely high.

Table 7 Product characteristic in relation to the level of use of the 10 most used organisational concepts

No.	Top 10 organisational concepts	Share of use in companies [%]	Products		
			Simple [%]	Medium complex [%]	Complex [%]
1	teamwork in production and assembly	78.7	10.4	46.3	43.3
2	standardized work instructions	77.5	10.3	52.9	36.8
3	ISO 9000 and other	77.5	9.2	52.3	38.5
4	5S	52.8	10.6	44.7	44.7
5	training to enhance creativity	52.8	9.1	50.0	40.9
6	TPM	49.4	6.8	50.0	43.2
7	continuous improvement of processes	43.8	0.0	64.1	35.9
8	TQM	40.5	5.6	52.7	41.7
9	integration tasks	40.5	5.6	41.6	52.8
10	program of staff development	39.3	5.7	57.1	37.2

Table 8 Product characteristic in relation to the high level of use of the 10 most used organisational concepts

No.	Top 10 organisational concepts	Share of high use [%]	Products		
			Simple [%]	Medium complex [%]	Complex [%]
1	ISO 9000 and other	66.7	8.7	52.2	39.1
2	standardized work instructions	46.4	9.4	59.3	31.3
3	5S	40.4	10.5	47.4	42.1
4	integration tasks	38.9	0.0	35.7	64.3
5	teamwork in production and assembly	38.6	11.1	40.7	48.2
6	continuous improvement of processes	38.5	0.0	53.3	46.7
7	TQM	36.1	0.0	61.5	38.5
8	TPM	25.0	0.0	45.5	54.5
9	program of staff development	22.9	0.0	37.5	62.5
10	training to enhance creativity	12.8	0.0	16.7	83.3

We can observe something similar for integration of tasks. This means that implementation of HRM concepts and specific forms of organising people in production (teamwork and integration of work) have a huge impact on companies' abilities to manufacture complex products. We can also see that within high use of six selected OI concepts companies do not produce simple products. This goes in line with the conclusion of general use of OI concepts.

Table 9 presents where companies get impulse for innovation from. We analysed the internal and external resources according to the three areas of innovation (new products, new technical production process and the new organisational concepts). Internal sources for innovation impulse are R&D department, production, sales department (contact with customers) and CEO. External sources for innovation impulse are customer-users, suppliers, research institutions and universities, conference-fairs.

If we focus on internal resources, we see that most impulses for innovation in the field of new product development come from sales (62.9 %) and the least from the production (7.9 %).Most impulses in the field of technical production process come from production (82 %) and the least from sales department (2.3 %). In the field of new OI concepts more than 60 % of the ideas come from CEO and the least from sales (10.1 %). The share of R&D does not exceed 50 % for any of three analysed areas.

If we look at external sources, we see that in the field of new product development, the highest share of ideas for innovation comes from customers (61.8 %) and least from research institutions and universities (6.7 %). In the field of new technical production process, the highest share of impulse for innovation comes from the suppliers (23.6 %), and the least from research institutions. In the area of innovation of new OI concepts, the largest share of ideas for innovation companies pick at conferences and trade shows (15.7 %). We can see that external sources are quite scarce for new technical production processes and OI concepts.

Table 10 depicts the impact of resources to innovate on the complexity of the products. We have chosen four internal resources (R&D, production, sales, CEO) and four external sources (customer-users, suppliers, research institute, conference-fairs). If we focus on internal resources, we can see that R&D, as an internal source, gives the highest share of impulse for medium complex products (60.6 %). The largest share of ideas for complex products comes from CEO`s (40.6 %). Looking at external sources, we see that the largest share of impulses for complex products comes from conferences and fairs (37 %). The largest share of impulses for medium complex products comes from research institutes and universities. To sum up, we did not find any significant relationship between product complexity and the impulses for product innovation. The only exceptions are perhaps research institutes and universities, and conferences and fairs, where companies do not look for ideas for simple products.

Table 9 Sources of innovation

Internal sources				
Field of innovations	R&D [%]	Production [%]	Sales department [%]	CEO [%]
New products	43.8	7.9	62.9	18.0
New technical production process	46.1	82.0	2.3	16.9
The new organizational concepts	14.6	24.7	10.1	61.8
External sources				
Field of innovations	Buyer/user [%]	Suppliers [%]	Research institutions [%]	Conferences, fairs [%]
New products	61.8	10.1	6.7	11.2
New technical production process	14.6	23.6	5.6	18.0
The new organizational concepts	7.9	4.5	9.0	15.7

Table 10 Impact of resources to innovate on the complexity of the product

	Complexity of products				Complexity of products		
Internal sources	Simple [%]	Medium complex [%]	Complex [%]	External soucses	Simple [%]	Medium complex [%]	Complex [%]
R&D	5.3	60.6	34.0	Buyer/user	12.3	54.4	33.3
Production	10.9	51.8	37.3	supplier	11.1	64.4	24.4
Sales department	10.8	52.9	36.3	Research, university	0.0	70.0	30.0
Top management	9.4	50.0	40.6	Conferences, fairs	0.0	63.0	37.0

5. Conclusion

The paper deals with issues relating to the prevalence and use of TI and OI concepts in Slovenian manufacturing industry, product complexity and sources of innovation. The purpose of the paper is to determine the use of TI and OI concepts of manufacturing companies and to analyse how they affect the characteristics of the product. According to the researchers Camisón and Villar-López this area is not studied enough [7], so the present paper contributes to research in this area. The results show that companies that have introduced specific technologies are continuously upgrading their performance. Unfortunately, majority of companies admits that they are not fully utilising these technologies up to their potential. Something similar can be observed for the high use of OI concepts. This means that manufacturing companies have a lot of room to improve their performance. Analysis of the impact of use of technical and OI concepts showed that general and high use of 10 most used innovation concepts has a positive impact on increasing complexity of products. We can observe that by increasing the number of introduced TI and OI concepts the share of simple products is decreasing, while the share of complex products is increasing. The high use of selected OI concepts has even stronger impact on the ability for companies to manufacture complex products. It is also a fact that with higher number of TI and OI concepts implemented the share of companies that have introduced new product to the market in the past three years also increases.

Our research results are unique since we found no studies that examine the relationship between the use of specific TI and OI concepts, product complexity and the ability to introduce new products to the market. Future research in this area will focus on finding correlations between innovation sources and product complexity. With new findings companies would have more data how to improve their chance for success.

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A hierarchical framework for index computation in sustainable manufacturing

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A B S T R A C T

Environmental regulations, the desire for market leadership and social stewardship along with pressing environmental crises have shifted manufacturing industries from focusing on traditional, purely profit-based strategies into pursuing the sustainability of manufactured products and manufacturing processes. However, assessing the sustainability levels of manufacturing industries poses a challenge due to the lack of holistic methods when in performing such assessments. In this area, current literature has embarked on computing an aggregate index for assessing sustainability performance. Nevertheless, approaches in computing sustainable manufacturing index are scarce in the literature. This paper presents a preliminary framework for computing a sustainable manufacturing index using the analytic hierarchy process. In this context, sustainability is interpreted from a triple-bottom line approach and the set of elements that comprise the index obtained from the US National Institute of Standards and Technology sustainable manufacturing repository. The use of this repository highlights a holistic approach in aggregate index computation as it offers a comprehensive list of elements of the triple-bottom line within the context of the manufacturing industry. Preliminary results have provided valuable insights into measuring sustainable manufacturing levels and could serve as a basic framework for index computation. The contribution of this work is on presenting a simple yet holistic approach towards computing a sustainable manufacturing index.

A R T I C L E I N F O

Keywords:
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1. Introduction

In this period when human activities pose environmental and social issues, solely profit or cost-based initiatives are insufficient to sustain manufacturing and its development through time. Stakeholders, which include customers, employees, investors, suppliers, communities, and governments [1], highlight manufacturing industry to focus on the performance of its manufactured products and manufacturing processes and to position them within the context of ongoing concerns on resource depletion, environmental impact, socio-economic issues and health problems. These stimulate manufacturing firms in broadening their perspectives beyond economic gains and to consider environmental and social benefits [2]. Firms seek to reconfigure physical, human, information and financial resources so that financial resources exiting the system are lower than those that enter it [1]. However, with these pressing concerns, other dimensions must be placed into the equation. This has prompted manufacturing firms to adopt approaches such as cleaner production, life cycle assessments, design for environment, environmental conscious manufacturing, and green technologies into more systemic approaches such as greening supply chains and industrial symbiosis. Synergy of these available tools may not adequately assist industry decision-makers at firm level who are required to assess and evaluate their operations in terms of internal and external impacts. These concepts, strategies and approaches constitute a much wider approach of sustainable manufacturing.

The US Department of Commerce defined sustainable manufacturing as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" [3]. This definition implies the existence of the three significant dimensions of sustainability, i.e. economic growth, environmental stewardship and social well-being. Manufacturing industries as key players in sustainable development initiatives, must at the macro level, deliver manufactured products with minimal impacts to the environment throughout product life cycles while maintaining social equity and reasonable economic growth. Thus, at the micro level, firms must ensure that their performance across and beyond the boundaries of the supply chain must be sustainable by (1) designing and producing products with processes that pose minimal environmental impacts, (2) taking on corporate initiatives that reduce cost, increase profit and provide higher returns on investments and (3) providing programs which enhance well-being of employees, customers and communities. These courses of actions must be organized in such a way that the total impact on the triple-bottom line is maximized. Current arguments suggest that manufacturing firms that promote sustainability focus in their business decision-making activities are more likely successful in their respective industry [4].

To address this challenge, manufacturing firms must adopt an approach that measures aggregate firm level sustainability performance. This enables firms to assess its sustainability level and to identify specific challenges and opportunities that firms must resolve and undertake in order to promote performance. This also brings insights on how initiatives must be specifically developed after learning firm's sustainability level. This may extend towards project selection, supplier selection, product development, process engineering, employee training programs and other decision-making areas that must be holistically integrated in order to promote firm-wide sustainability. Current literature offers potential approaches in terms of measuring sustainability level through the use of indicators and indices [1]. There are increasing interests on establishing sustainability indicators which enable firms in measuring sustainability initiatives and in establishing concrete, long term plans for sustainable manufacturing. Nevertheless, the fundamental guideline on developing such indicators and indices is that they must be operational and comprehensive enough to account for the complexity of the requirements of sustainability. Thus, this paper attempts to present a methodology in computing sustainable manufacturing index as a measurement for an aggregate sustainability level. This work adopts the comprehensive sustainability indicators set developed by Joung et al. [2] from a careful integration of 11 established indicators sets. Following the hierarchical nature and the multi-dimensional and multi-level sustainability indicators set of Joung et al. [2], the use of analytic hierarchy process (AHP) becomes highly appropriate and helpful. Analytic hierarchy process provides a multi-criteria decision-making platform that allows decision-makers to allocate weights for each element in a decision model which is necessary in index computation. The contribution of this work lies in presenting a holistic framework of index computation that attempts to measure sustainability at firm level.

2. Literature review

2.1 Sustainable manufacturing

Sustainable manufacturing is oftentimes attached to some other terms such as business sustainability and corporate sustainability. In one representative definition, business sustainability is defined as "adopting business strategies and activities that meet the need of the enterprise and its stakeholders today while protecting, sustaining and enhancing the human and natural resources that will be needed in the future"[5]. On the other hand, corporate sustainability is defined also as "meeting the needs of the firm's direct and indirect stakeholders without compromising its ability to meet future stakeholder needs as well" [6] and "demonstrating the inclusion of social and environmental concerns in business operations and in interactions with stakeholders" [7]. These two terms are similar and interchangeable to some extent. They pose the need of addressing the triple-bottom line through corporate policies, strategies and directives. While such definitions are conceptual, they do not provide options into how firms must manage its efforts and resources quantitatively in promoting sustainability at the corporate level. While corporate sustainability holds at the business level, sustainable manufacturing encompasses this concept by focusing on manufactured products and manufacturing processes and their impacts to various stakeholders.

Since sustainable manufacturing focuses on the impacts of products and processes, improving environmental stewardship and sustainability while maintaining profitability, is increasingly viewed by manufacturing firms as a strategic approach [1]. This view holds that environmental regulations of products and process must not be considered as constraints but part of the overall strategic goal of sustenance and business leadership. Furthermore, promoting employee and community development programs are not merely developed for improving business image but part of the long-term sustainability roadmap.

2.2 Sustainability indicator sets

The notion of sustainability is widely pronounced in literature; nevertheless expressing it in concrete, operational terms remains difficult [8]. A significant approach of measuring and assessing sustainability is through the use of sustainability indicators. Indicators help identify the status of sustainability, the progress made towards this objective, the challenges and problems in moving towards this objective as well as the measures that must be adopted to address these challenges and problems [1]. Roshen and Kishawy [1] argue that an integrated, multidimensional sustainability indicators set that highlights the triple bottom line is necessary to achieve sustainability. Standard indicators will provide a reliable and repeatable means for manufacturing firms when they evaluate and allow comparisons between products, processes, firms, sectors, or countries in view of sustainable manufacturing [2]. However, little research has been conducted on the indicators used to convey quantitative information in sustainability reports [9].

In this line, a number of sustainability indicator sets were proposed by international committees, individual firms and private institutions. These are the Global Report Initiative [10], the Dow Jones Sustainability Indexes [11], the Institution of Chemical Engineers Sustainability Metrics [12], United Nations-Indicators of Sustainable Development [13], the Wuppertal Sustainability Indicators [14], the 2005 Environmental Sustainability Indicators [15], the European Environmental Agency Core Set of Indicators [16], the Environmental Performance Index [17], the Organization for Economic Cooperation and Development Core Environmental Indicators [18], the Japan National Institute of Science and Technology Policy [19], the Ford Product Sustainability Index [20], the Environmental Pressure Indicators for European Union [21], the General Motors Metrics for Sustainable Manufacturing [22, 23], the Wal-Mart Sustainability Product Index [24] and the International Organization for Standardization Environment Performance Evaluation Standard [25]. All of these indicator sets comprise indicators that measure a specific area in sustainability. They are categorized into groups that form the dimensions of sustainability. Most of these indicator sets belong to environmental dimensions [8] while others are country or regional-based specific. Frequently, most economic indicators are net sales, costs of purchased goods, materials, services, total payroll and benefits. Most environmental indicators are energy and water consumption, carbon dioxide emissions, internal initiatives to improve energy efficiency. Most social dimension indicators are workplace health and safety policies and measures, employee education and skill management, and the benefits that employees receive from the organization beyond those that are legally mandated [9].

With these various and complex sets, identifying which set(s) of indicators or a mix of sets applicable in sustainable manufacturing poses difficulty. Thus, a need to select and prioritize indicators is required [26]. A number of characteristics of sustainable manufacturing indicators are the following: (1) relevance, revealing necessary information about a system or process (2) understandability, straightforward and readily understood by experts and non-experts and (3) reliability, providing information that is trustworthy and (4) assessable, based on available and accessible data [1]. The most comprehensive evaluation and investigation of sustainable manufacturing indicators is provided by Joung et al. [2] which eventually became a standard held by the U.S. National Institute for Standards and Technology (NIST). Joung et al. [2] combined indicators from 11 known indicator sets [10, 11, 13, 15-21, 25]. They processed them logically and categorized them into criteria and sub-criteria that form a hierarchy. This builds up 212 indicators from five dimensions of which 77 indicators are from environmental stewardship, 23 for economic growth, and 70 for social well-being dimension, 30 for performance management and 12 for technological advancement management [2]. The repository of these indicators is found in NIST's Sustainable Manufacturing Indicator Repository (SMIR) website [27].

2.3 Sustainable manufacturing index

Indices are significant pieces that can be aggregated by weight-based mathematical methods into a single score [2]. With this single score, a sustainability level can be set and used as a metric for performance [2]. There are practical significant gains a manufacturing firm can have out of a sustainable manufacturing index. This enables manufacturing decision-makers for trade-off analysis in sustainability decisions given diverse interests of stakeholders [1]. It means that a firm can control which category or sub-category must be given relevant attention so that long term objectives are met and issues on sustainability are addressed. Sustainable manufacturing index also provides manufacturing firm a view on its strengths and weaknesses. Furthermore, sustainable manufacturing index can be used as a risk-mitigating criterion for upstream manufacturers in the supply chain by identifying and ranking potential business partners based on their sustainability performance [28]. Despite of this importance of developing methodology for measuring sustainable manufacturing performance level, this is scarcely provided in literature. There is no consensus yet on measuring sustainability performance [8, 26, 28] and little has been reported on the quantitative modelling on overall sustainable manufacturing level [2, 29].

There were attempts made by previous works. De Silva, et al. [29] proposed a new scoring method for product sustainability index (PSI) through 6 sustainability elements defined in 44 influencing factors described in 24 sub elements. The influencing factors (or indicators) are equally weighted and PSI is computed as the weighted average of sub elements. Ghadimi, et al. [30] developed a product sustainability assessment methodology using fuzzy analytic hierarchy process (AHP). They proposed an algorithm termed as weighted fuzzy assessment method (WFAM) to achieve improved product sustainability index by addressing the current sustainability index. Jaafar et al. [31] presented a comprehensive procedure for computing PSI by calculating the weighted sum of different sub elements within the triple-bottom line for each life cycle stages (pre-manufacturing, manufacturing, use and post-use). Gupta et al. [26] developed a procedure for specifying and streamlining sustainability assessment without compromising significantly on comprehensiveness of product sustainability involving the use of AHP to prioritize sustainability elements based on the unique needs for a particular design scenario. However, these methodologies are focused only on product sustainability. Other works involving measuring or enhancing sustainability performance were the use of close-loop 6R methodology in the product life-cycle [4], introducing linear programming extended Data Envelopment Analysis [28], using systems approach by involving technology, energy and material for environmentally sustainable manufacturing through LCA methodology [32] and providing strategic sustainability decision-making approach by recommending additional analytical support systems [33]. Despeisse et al. [34] highlight a down-scaling of the concept of industrial symbiosis at a factory level. They presented a focus on overall performance of manufacturing systems using a model of MEW (Material, Energy, Wastes) in three components of manufacturing system – manufacturing operations, supporting facilities and surrounding buildings.

2.4 Summary of the review

Based from the preceding review, there is a gap in literature on the development of methodology of measuring sustainable manufacturing index. This index is vital for manufacturing firms at it provides an overview on their sustainability level and may be used as risk-mitigating criterion for long term coordination in the supply chain. This paper provides a methodology of computing sustainable manufacturing index from a repository of indicators in US National Institute for Standards and Technology [27] as a comprehensive set of indicators drawn from established and known indicator sets. US NIST [27] indicator repository is structured as a hierarchy of categories and subcategories. In order to complement with the hierarchical structure of the sustainable manufacturing framework of Joung et al. [2], this paper adopts the use of analytic hierarchy process (AHP) in computing weights of categories and sub-categories. AHP is a powerful tool in multi-criteria decision analysis especially in hierarchal decision-making. AHP, developed by Saaty [35], requires decision-makers to provide pairwise comparisons of elements. By solving an eigenvalue problem proposed by Saaty [35], weights can be computed in the hierarchy [35]. Due to the difficulty of transforming the triple-bottom line into purely quantitative scales [2], AHP can capture the subjective judgments of decision-makers and then transform them into numerical values. A review of the application of AHP in operations management reports 21 published papers in measuring and improving activities on products, process and systems [37]. A review of modelling approaches in sustainable supply chain management which is multi-criteria in nature reveals AHP as one of the effective methodologies in decision-making [38]. These reviews show that AHP is widely used in decision-making.

3. Methodology

3.1 Research framework

The framework for this paper is described in Fig 1. The indicators set adopted in this paper is the one provided by Joung, et al. [2] which is now maintained by the US National Institute for Standards and Technology [27]. This is chosen for a number of reasons: (1) it is a combination of 11 established indicator sets [10-11, 13, 15-21, 25] published by recognized international bodies, manufacturing leaders, research and private institutions, (2) the selection of the indicators to be included in the US NIST standards undergoes a systematic and rigid process, (3) sustainable manufacturing framework developed by Joung, et al. [2] is hierarchal which provides groupings of indicators into sub categories, sub categories into categories, and categories into sustainable manufacturing dimensions and (4) it is the most comprehensive indicator set recently developed. The choice of the indicator set does not affect the methodology of computing sustainable manufacturing index. However, it has implications regarding the structure of sustainable manufacturing and its components which may alter the value of the index. Improvement in the contents of the indicator set does not affect the process of obtaining the sustainable manufacturing index.

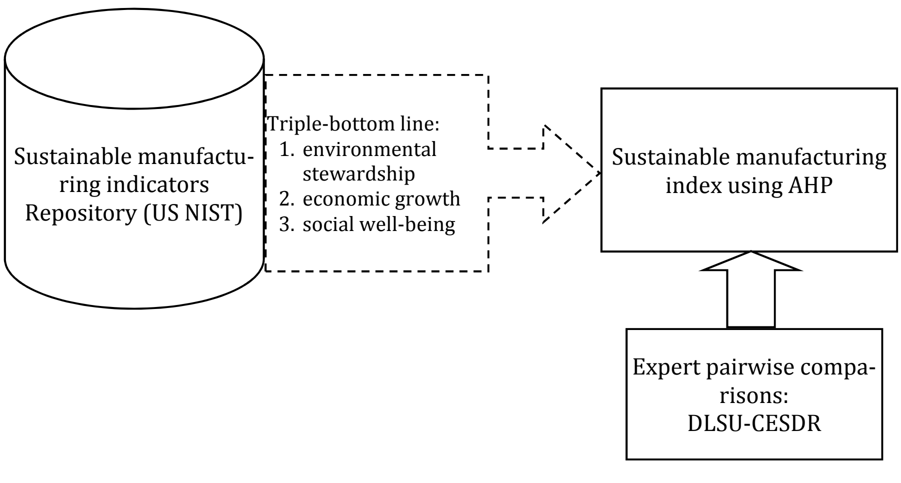

Fig. 1 Methodological approach of the study

Indicators set provided by US NIST [27] defines sustainable manufacturing in five dimensions namely, environmental stewardship, economic growth, social well-being, performance management, and technology advancement management. The last two dimensions appeared because of the presence of indicators in these two aspects [2] from the established 11 indicator sets being analysed. However, Joung et al. [2] maintained that these two aspects are inherent in the triple-bottom line and can be merged until further revisions of the indicator set are done. In this paper, the triple-bottom line approach is maintained with particular emphasis on the first three dimensions with all its categories, sub-categories and indicators. This choice is cognizant with various works in literature which promote the triple-bottom line [4, 8, 9, 26]. The hierarchical structure of sustainable manufacturing as depicted in US NIST [27] is presented in Fig. 2. There are 4 levels in the structure denoted as level 0, level 1, level 2 and level 3 for sustainable manufacturing index, sustainable manufacturing dimensions, criteria and sub-criteria, respectively. Each sub-criterion in level 3 has distinct number of indicators as indicated in Fig 2. The number of indicators varies with the sub-criterion with 1 as the least number of indicators. Note that environmental stewardship has 77 indicators, economic growth has 23 indicators and social well-being has 70 indicators with a total of 170 indicators were used in this paper.

3.2 Computation

Components in each level of Fig. 2 have specific weights which correspond to the degree of importance in sustainable manufacturing. We find it necessary to have an outside expert in sustainable manufacturing researches to assess and provide pairwise comparisons on the elements in Fig. 2 as defined in the AHP methodology.

To achieve expert-based results, we invite De La Salle University Centre for Engineering and Sustainable Development Research (DLSU-CESDR) to provide us with pairwise comparisons on each level in Fig 2. De La Salle University has been one of leading academic institutions that is active in sustainable development research since a decade ago. Results are expected to be valid as far as their expert knowledge and experience in the field are concerned. Individual weights for level 1, 2 and 3 are then computed using Saaty's [35] method. Consistency ratio (C.R.) is also computed for each pairwise comparisons matrix which explains the degree of consistency in decision-maker's judgment. Acceptable C.R. value is 10 % (0.10) as suggested by Saaty [39]. Sample pairwise comparisons matrix with the computed weights and consistency ratio is provided in Table 1.

Table 1 shows an actual pairwise comparison matrix elicited by DLSU-CESDR. The sample matrix is derived from comparing the relevance of the three sustainable manufacturing dimensions. There are a total of 14 pairwise comparison matrices in this paper. For instance a score of 2 in row 2 column 1 suggests that experience and judgment slightly favoured economic growth over environmental stewardship (see Saaty [39] for a detailed discussion on Pairwise Comparison Scale). The column weights are the relative weights computed using the eigenvector approach of Saaty [39]. A C.R. value of 0.0 means perfect consistency on the decision-maker's judgment [39].

As soon as each of the elements in Fig 2 has computed priority weights, then a weight distribution in the hierarchical structure is obtained. The sustainable manufacturing index of any manufacturing firm can be computed through a case study. A questionnaire that contains a list of all 170 indicators which the firm's representative must rate from 0-10 with 10 as the highest and 0 as the lowest is sent to a firm. To provide a discussion with regard to the computation of the weights, Table 2 provides a sample detail. Table 2 is derived from environmental sustainability dimension under the pollution category and under Toxic Substance sub-category. This sub-category has 11 indicators as shown in Fig. 2. Actual score column lists scores provided by the firm on the level of their performance on an indicator. For instance, lead used indicator has a score of 1. It means that the company has relatively fewer amount of lead used in their products and processes. Next, we used an absolute method of translating the actual score to a normalized score. The indicators provided in the subcategory denote a negative performance in the category. Values from 0 to 10 mean that the performance in this sub-category is deteriorating. By providing a rating of 1 on these indicators means a -1 to the performance. To come up with a positive value, we add algebraically the actual rating which is -1 to 10 to obtain the normalized score which is 9 in this case. A value of 9 in our rating means that the company has relatively higher environmental performance. This is referred to as the absolute method. This value is then multiplied with the weight obtained in the AHP method (in this case, toxic substance has a weight of 0.348 to get the computed index. These indicator indices are then averaged to get the Toxic Substance Index. A value of 2.025 means that on the rate from 0-10 the company has less performance in toxic substance. This value is brought up in the hierarchy by multiplying with the respective category weight and the weights of the sustainable manufacturing dimensions. Performing this process to all sub-categories, the sustainable manufacturing index can be computed.

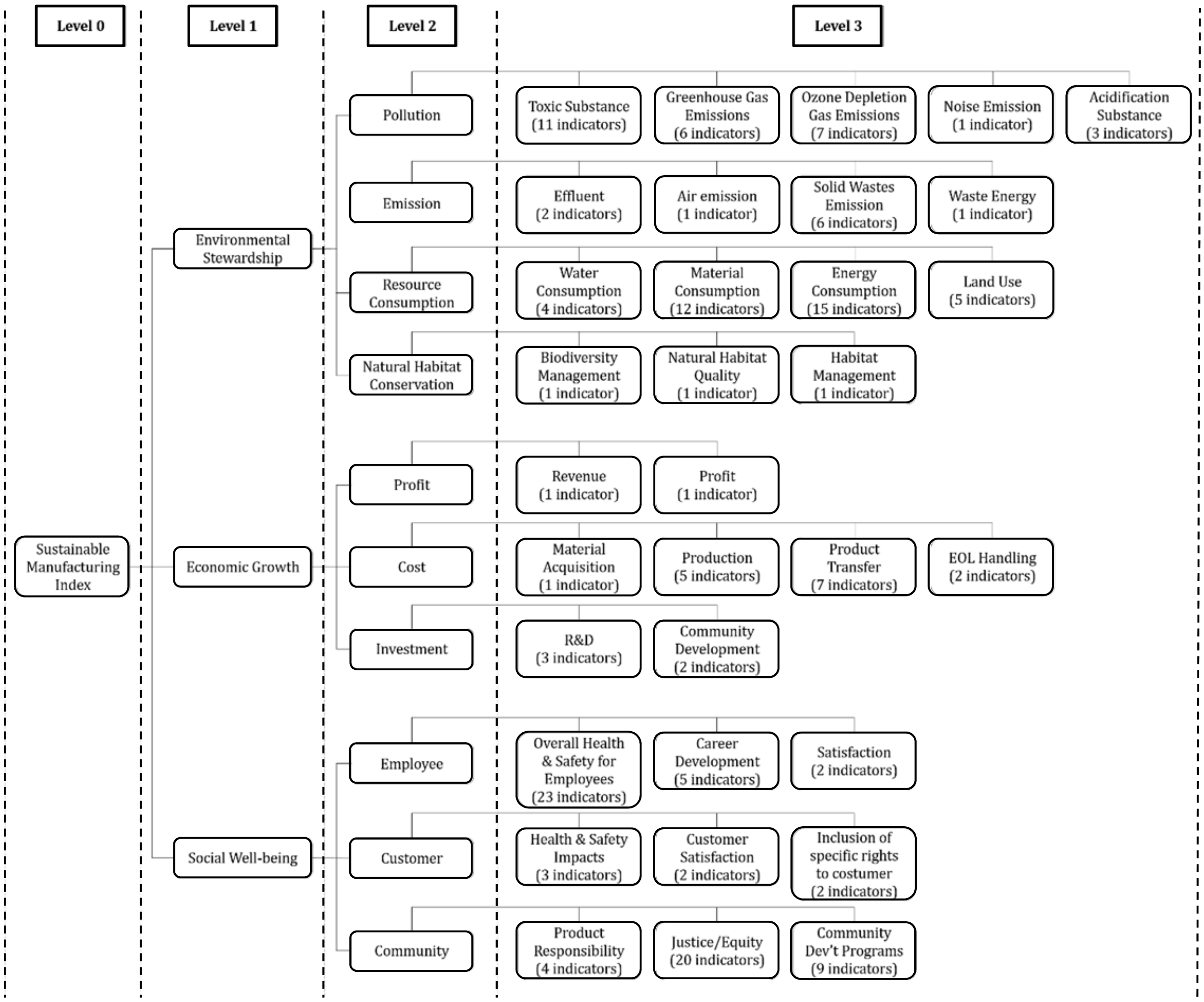

Fig. 2 Sustainable manufacturing hierarchal structure

Table 1 Actual sample of pairwise comparisons matrix with computed weights and consistency ratio

	Environmental stewardship	Economic growth	Social well-being	Weight	Consistency ratio (CR)
Environmental stewardship	1	1/2	1/2	**0.2**	**0.0**
Economic growth	2	1	1	**0.4**	
Social well-being	2	1	1	**0.4**	

Table 2 Sample detail of case study computation

Dimension: Environmental Stewardship Category: Pollution				
Sub-category: Toxic Substance	Actual score	Normalized score	Weight	Computed index
Lead (Pb) used	1	9	0.348	3.132
Mercury (Hg) used	1	9	0.348	3.132
Hexavalent chromium (Cr6+) used	1	9	0.348	3.132
Cadmium (Cd) used	1	9	0.348	3.132
Polybrominated biphenyl flame retardants (PBB) used	7	3	0.348	1.044
Polybrominated diphenyl ether flame retardants (PBDE) used	7	3	0.348	1.044
Eco-toxic substance effluent	6	4	0.348	1.392
Eco-toxic waste produced	6	4	0.348	1.392
Number of WEEE-related registrations	5	5	0.348	1.740
Chemical spills	6	4	0.348	1.392
Eco-toxic substances emissions	5	5	0.348	1.740
				2.025

4. Results and discussion

Using Saaty's Fundamental 9-point scale [39], pairwise comparisons were performed on sustainable manufacturing dimensions, criteria and sub-criteria. There were 34 pairwise comparison matrices elicited by DLSU-CESDR. Using the eigenvector method proposed by Saaty [39], respective weights for each of the elements can be computed. Complete weight distribution using the AHP is illustrated in Table 3.

The total weight of all sub-criteria in particular criterions as well as the total weight of criteria in a particular sustainable manufacturing dimension are equal to 1.0. In a particular sub-criterion there are a number of indicators ranging from 1 up to 23. The complete discussion of indicators and relevant explanation of criteria and sub-criteria as to their meanings, methods of measurement are discussed in the NIST SMIR website [27]. Weight allocation of all the elements in the sustainable manufacturing hierarchy is completed. We apply these weight allocations to a case firm in coming up with a sustainable manufacturing index using the methodology described in the previous section. C.R. < 0.10 for all pairwise comparisons performed in this work. Thus, all judgments of the pairwise comparison matrices are consistent.

Table 4 shows a summary of case firm's sustainable manufacturing index with comparison to the ideal index shown in Table 3. It is shown that the case firm's performance is just halfway of the ideal sustainability score. It is apparent that the case firm's performance can be treated as fair with several rooms for improvement. Identifying specific areas with rich potential for improvement can be identified using the proposed sustainable manufacturing index approach. The proposed methodology is beneficial for firms as (1) it provides a comprehensive approach in assessing firm wide sustainability level, (2) it offers a platform in determining specific areas which are potential for improvement, (3) it is simple and comprehensible for non-technical decision-makers, and (4) it provides inputs to policy making and long term strategic actions. In general, firms can apply the proposed method in assessing sustainability level. However, these conditions must exist: (1) decision-makers must be cross functional who could provide inputs from various perspectives, (2) decision-makers must be highly knowledgeable of firm's core products and processes, (3) decision-makers must make assessment based on hard data available from the firm.

Table 3 Sustainable manufacturing weight allocation using analytic hierarchy process

Elements	Priority weight		
Environmental stewardship			0.200
Pollution		0.351	
Toxic substance	0.348		
Greenhouse gas emissions	0.348		
Ozone depletion gas emissions	0.120		
Noise	0.065		
Acidification substance	0.120		
Emissions		0.351	
Effluent	0.231		
Air emissions	0.462		
Solid waste emissions	0.231		
Waste energy emissions	0.077		
Resource consumption		0.161	
Water consumption	0.300		
Material consumption	0.100		
Energy/electrical consumption	0.300		
Land use	0.300		
Natural habitat conservation		0.137	
Biodiversity management	0.500		
Natural habitat quality	0.250		
Habitat management	0.250		
Economic growth			0.400
Profit		0.400	
Revenue	0.500		
Profit	0.500		
Cost		0.400	
Materials acquisition	0.333		
Production	0.333		
Product transfer to customer	0.167		
End-of-service-life product handling	0.167		
Investment		0.200	
Research and development	0.333		
Community development	0.667		
Social well-being			0.400
Employee		0.250	
Employees health and safety	0.600		
Employees career development	0.200		
Employee satisfaction	0.200		
Customer		0.500	
Health and safety impacts from manufacturing and product use	0.200		
Customer satisfaction from operations and products	0.400		
Inclusion of specific rights to customer	0.400		
Community		0.250	
Product responsibility	0.333		
Justice/equity	0.333		
Community development programs	0.333		

Table 4 Summary of case firm's index

Sustainability dimension	Ideal index	Case firm index
Environmental stewardship	2	0.923
Economic growth	4	2.131
Social well-being	4	2.041
Sustainable manufacturing index	10	4.173

5. Conclusion and future work

Using analytic hierarchy process, weights for the sub-criteria, criteria and sustainable manufacturing dimensions in a hierarchically designed sustainable manufacturing were obtained. These elements, including respective indicators, can be found from the US National Institute of Standards and Technology (US NIST) Sustainable Manufacturing Indicators Repository (SMIR) [27]. The weights are normalized from 0 to 1. The weights in the hierarchy assume the portion of contribution of that particular element (sub-criteria, criteria or dimensions) to the sustainable manufacturing score. By way of viewing them as contribution, these values can be considered as upper limit or ideal value of the element. The method integrates both objective and subjective judgments of decision-makers in assessing firm's sustainability performance. Managers can easily access the method due to its simple analytical procedure. Thus, this paper provides a preliminary framework in computing firm-wide sustainable manufacturing index.

Further works on this paper are significant. First, one can list down all the sub-criteria in decreasing order of their contribution to sustainable manufacturing index. From here, managers can prioritize which indicators impact sustainability. Second, optimization methods can be used to determine strategies of a particular manufacturing firm that will optimize sustainability using the weights obtained from AHP. Lastly, one could investigate the interrelationships of the criteria and sub-criteria using analytic network process (ANP). The existence of interrelationships in criteria and sub-criteria will provide significant information to manufacturing firms as they address complexity in decision-making.

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Calendar of events

- International Conference on Industrial Engineering and Operations Management (IEOM 2015), Dubai, United Arab Emirates, March 3-5, 2015.
- 6th International Conference on Mechanical, Industrial, and Manufacturing Technologies (MIMT 2015), Melaka, Malaysia, March 6-7, 2015.
- IEEE International Conference on Industrial Technology, Seville, Spain, March 17-19, 2015.
- 4th International Conference on Manufacturing and Industrial Engineering (ICMIE 2015), Singapore, March 21-23, 2015.
- The Seventh International Conference on Adaptive and Self-Adaptive Systems and Applications (ADAPTIVE 2015), Nice, France, March 22-27, 2015.
- CAEM2015 – 2015 International Conference on Composite Materials and Advanced Energy Materials, Guangzhou, China, March 28-29, 2015.
- Sustainability in Packaging 2015, Orlando, United States, March 31 – April 2, 2015.
- International Conference on Mechanical and Manufacturing Engineering, Kancheepuram, India, April 2-3, 2015.
- ICEMPM 2015: International Conference on Engineering, Manufacturing and Production Management, Los Angeles, USA, April 3-4, 2015.
- ICSCLM 2015: International Conference on Supply Chain and Logistics Management, Dubai, United Arab Emirates, April 8-9, 2015.
- 20th International Conference on Wear of Materials, Toronto, Canada, April 12-16, 2015.
- The 4th International Conference on Manufacturing Engineering and Process (ICMEP 2015), Paris, France, April 13-14, 2015.
- ICMCTF'15 – International Conference On Metallurgical Coatings & Thin Films, San Diego, United States, April 20-24, 2015.
- 2nd International Conference on New Technologies (NT 2015), Mostar, Bosnia and Herzegovina, April 24-25, 2015.
- IEEE International Conference on Technologies for Practical Robot Applications, Woburn, Massachusetts, USA, May 11-12, 2015.
- IFAC Symposium on Information Control in Manufacturing (INCOM 2015), Ottawa, Canada, May 11-13, 2015.
- 14th International Conference on Tribology (SERBIATRIB 2015), Belgrade, Serbia, May 13-15, 2015.
- International Conference on Advances in Mechanical Engineering (ICAME 2015), Istanbul, Turkey, May 13-15, 2015.
- IEEE International Conference on Robotics and Automation, Seattle, Washington, USA, May 25-30, 2015.
- 2nd International Conference on Industrial Engineering, Management Science and Applications (ICIMSA 2015), Tokyo, Japan, May 26-28, 2015.
- 6th International Conference on Modeling, Simulation and Applied Optimization, Istanbul, Turkey, May 27-29, 2015.

- ICIT 2015: International Conference on Industrial Technology, Vienna, Austria, June 21-22, 2015.
- 10th International Conference on Additive Manufacturing & 3D Printing, Nottingham, UK, July 7-9, 2015.
- AIM – 2015 IEEE International Conference on Advanced Intelligent Mechatronics, Busan, South Korea, July 7-11, 2015.
- ICME 2015: International Conference on Manufacturing Engineering, Stockholm, Sweden, July 13-14, 2015.
- 27th European Conference on Operational Research (EURO 2015), Glasgow, UK, July 12-15, 2015.
- The 5th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2015), Colmar, France, July 21-23, 2015.
- XXIV International Materials Research Congress (IMRC 2015), Cancon, Mexico, August 16-20, 2015.
- IEEE 20th Conference on Emerging Technologies & Factory Automation, Luxembourg, Luxembourg, September 8-11, 2015.
- ICMSE 2015: International Conference on Manufacturing Science and Engineering, Berlin, Germany, September 14-15, 2015.
- IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2015), Hamburg, Germany, September 28 – October 2, 2015.
- ASME – International Mechanical Engineering Congress & Exposition (IMECE), Houston, Texas, United States, November 13-19, 2015.

Notes for contributors

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