Int j simul model 18 (2019) 1, 72-85
ISSN 1726-4529 Original scientific paper

ECO-DESIGN OF FIXTURES BASED ON LIFE CYCLE AND COST ASSESSMENT

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Abstract

The paper presents the new model for eco-design of fixtures based on life cycle and cost assessment. Four fixture types with different mechanical and physical properties as well as different manufacturing costs have been evaluated. The life cycle results show that the environmental impact is closely related to the mass of steel needed for fixture manufacture. On the other hand, the fixture with the largest environmental impact had the smallest total fixture cost and vice versa. The results show that it is possible to implement environmental and cost analysis in fixture design process and to enable comparative analysis of fixture constructions by three standpoints, technical, environmental and economic.

(Received in September 2018, accepted in January 2019. This paper was with the authors 1 month for 1 revision.)

Key Words: Eco-Design, Eco-Efficiency, Fixtures, Life Cycle Assessment

1. INTRODUCTION

Modern manufacturing system is characterized with wide product’s assortment, high frequent changes in manufacturing programme, requirements for continual improvement of products quality, reduced manufacturing times and costs, etc. One of the most critical features of a modern manufacturing system is the ability to design and produce lots of high-quality products in the shortest possible time. Rapid launching of a novel product which beats the competition to the market represents a key factor in providing larger market share, and higher profit margins. All this requires development of flexible manufacturing system. The manufacturing processes include [1]: casting, forming, shaping, joining, machining, etc. Large numbers of products are processed in total by the manufacturing processes. Therefore, manufacturing processes have crucial impact on all products' quality properties [2]. Beside the traditional requirements (technical requirements) that each product should fulfil, products have to satisfy environmental requirements also [3].

In the field of manufacturing, especially in the machining, there have been large number researches that investigated the impact on the environment. For, example, Rajemi et al. [4] developed a methodology for optimising the energy footprint. The total energy of machining by the turning process was modelled and optimised to derive an economic tool-life that satisfies the minimum energy footprint requirement. Bhushan [5] evaluated the contribution of cutting parameters during turning on the power consumption and tool life by using response surface methodology. Gaha et al. [6] described manufacturing process planning eco-design approach based on feature technology and Life Cycle Assessment (LCA). Aramcharoen and Mativenga [7] studied the energy intensity in machining process and developed a methodology to predict the energy consumption considering toolpath strategies,

https://doi.org/10.2507/IJSIMM18(1)463

cutting mode and tool wear. Hassine et al. [8] presented operations and cutting conditions during turning that allow manufacturing with respect of ecological, and constraints. Murray et al. [9] developed a parameterized process model for computer numerical control grinding, which enabled the calculation of life cycle inventory (LCI) data. Palčič et al. [10] mapped the adoption of technologies for energy reduction and resources consumption in production. Some specific relationships between energy efficient technologies and environmental management systems ware presented. Winter et al. [11] proposed a stepwise approach to compare alternative enabling factors in conjunction with the process parameters in order to reduce the costs and environmental impacts of a grinding process under consideration of technological requirements. Further, Winter et al. [12] provided an overview of the materials and energy needed during the different life phases of a cubic boron nitride grinding wheel. Silva et al. [13] used a modelling approach that combines LCA with design of experiments to investigate cylindrical plunge steel grinding. Liu et al. [14] investigated emissions and environmental impact induced by the machine tool's energy consumption and the cutting tool embodied energy. Deng et al. [15] investigated the quantification calculation method of the carbon emissions during grinding. Li et al. [16] investigated the environmental impacts of cutting tools from the life cycle aspect based on the material and energy consumption during the material extraction, manufacturing, use, and recycling. Bagaber and Yusoff [17] presented a methodology to optimize machining parameters and minimize power consumption in dry turning. Zhang et al. [18] proposed control method for carbon footprint of machining process to minimize the carbon emissions. Filleti et al. [19] presented a study of grinding process, along with the use of a combined LCA and monitoring system to evaluate the consumption of energy, tooling, cutting fluid and compressed air. Li et al. [20] presented an integrated approach of process planning and cutting parameter optimization to minimize the total energy consumption of CNC machining. Chen et al. [21] presented a differential model of grinding energy consumption that takes account of dynamic grinding force, forced-vibration induced by the eccentrically grinding wheel rotation, and the phase difference between adjacent regenerative surface waviness. Liu et al. [22] developed a method to model cumulative energy demand in milling as a function of energy consumption of machine tool, workpiece material, cutting tool, and coolant.

Other examples of implementation of environmental aspects into manufacturing can be found in review papers [23-26]. Previously presented researches tried to optimize the technological, economic, and environmental objectives in manufacturing system, above all from the point of reduce the environmental impact on manufacturing, i.e. optimize manufacturing processes and operations, selection of a suitable manufacturing strategy, minimize material consumption, minimize energy consumption, minimize carbon emissions, minimize the negative impact of cutting fluids, etc. However, the level and trend of further development and implementation of environmental aspects into manufacturing should be viewed from the light of all factors – materials, process, operations, machine tools, tools, fixtures, etc. None of the previous studies did not addressed to the environmental aspects of the fixtures. Fixtures are an essential part of every manufacturing system. Fixture is becoming increasingly important considering that they directly impact accuracy, productivity, and quality. They have a high frequency of design. The design of a fixture is a highly complex process. For a given workpiece, multiple fixture solutions may exist [27]. Approximately 40 % of rejected parts are due to dimensioning errors that are attributed to poor fixturing design [28]. Further, the costs associated with the design and manufactures of fixtures are sizeable, accounting for some 10-20 % of the total cost of a manufacturing system [29]. Fixtures could have significant influence on the total processing time by improving the flexibility of manufacturing systems [30].

In contrast to previous investigations, the subject of this research is development of the new model for fixture design which implements eco-design in the fixture life cycle. The basic idea is to integrate the environmental aspects into the fixture design and manufacturing process, that is, to improve the quality from the perspective of reducing the impacts on the environment. Thereby, fixture construction has to fulfil technical requirements. It is necessary to manufacture a fixture that will ensure efficiency and quality identical to those of existing fixtures with improvements in terms of environmental aspects and minimal extra costs. In LCA research, cost assessment and eco-efficiency are applied with the aim of tackling fixture eco-design.

2. FIXTURES DESIGN

2.1 Current situation

Fixture life cycle consists of: planning, design, manufacture, exploitation, and storage. Key phase in fixture life cycle is fixture design. Traditionally, the fixtures are designed in phases, step by step (Fig. 1).

Important factors for fixture design are technical requirements. Input information contains technical requirements, such as: workpiece information, manufacturing process information, and manufacturing management information. During the realization of design phases and activities, case sensitive technical requirements have to be fulfilled for each fixture.

During the fixture design, it is necessary to comply with basic design phases, such as (adapted from [31]):

- *Setup planning*.The first step in setup planning is identification of machining setups. Identification of setups implies determination of workpiece surfaces intended for machining, as well as the needed activities within each machining operation and sequences. Workpiece surfaces are determined for each identified setup. These surfaces enable locating and clamping.
- *Fixture planning*. Fixture planning implies determination of fixture layout plan based on technical requirements which are appointed for future fixture construction. Fixture layout plan defines location and clamping scheme for each setup. Afterwards fixture layout optimization procedure is realized. Fixture layout optimization implies application of adequate methods aiming to define the optimal space order of fixture elements regard to workpiece.
- *Fixture elements and construction design*. The first step in fixture element and construction design is conceptual and detailed fixture element design. The following elements can be included in fixture construction: locating elements, supporting elements, clamping elements, body element, connecting elements, tool-guiding elements, aligning elements, and additional elements. In conceptual design phase of fixture elements, type and number of fixture elements is defined. In detail fixture element design phase, material and geometrical properties (dimensions, tolerance, and geometrical specifications) for each fixture element are defined. After all fixture elements have been defined, fixture construction can be assembled.
- *Fixture verification*. In fixture verification, the designed fixture is being checked if it fulfils the corresponding technical requirements. This verification includes checking of stiffness, deformations, collision detection, usability, affordability, etc.

On the output side, after the fixture designer carries out all the fixture design phases and activities, large number of fixture constructions is acquired. For each fixture, construction and bill of materials (BOM) are known. BOM contains data about fixture elements, i.e. data about fixture element's manufacturing processes, quantities (number) of elements, element's material, and mass of each element. Finished fixture constructions fulfil technical requirements but do not consider costs and negative impact on the environment. Finally, fixture designer selects one of the possible fixture solutions by free choice, and production will be realised as a next life cycle stage for the selected solution.

Previous researches in field of fixture design have been focused on solving and optimisation of previously identified phases. Numerous methodologies have been applied in order to solve the fixture design process [28, 29, 31-33].

None of the previous researches have considered impacts on the environment to the fixture design process. Having in mind previously stated, aim of this research is to integrate assessment of environmental impacts and costs into fixture design process in order to get closer to optimal fixture construction solution from point of technical, environmental, and economic aspects.

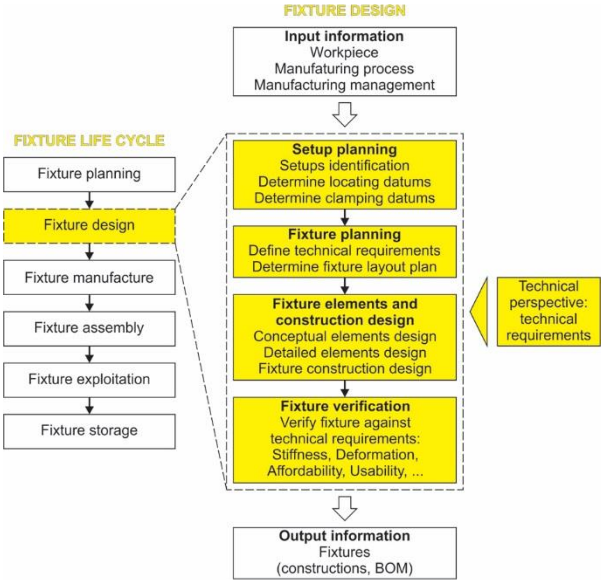


Figure 1: The fixture design process (adapted from [31]).

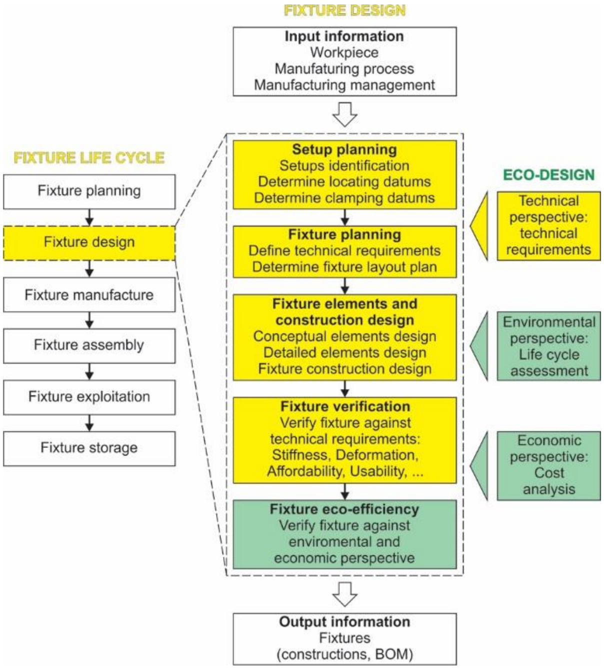


Figure 2: Model for implementation of eco-design into fixture design process.

2.2 New fixture design model – fixture eco-design model

In order to improve fixture design process, model in Fig. 2 is proposed. Model consists of previously defined conventional fixture design phases, with difference of implementation of environmental and economic requirements into design process. This is realized in final design phase, named fixture eco-efficiency.

Model unifies technical, environmental and aesthetic requirements that fixture has to fulfil. Basic idea is that environmental and economic requirements are applied at all potential fixture solutions that already fulfilled technical requirements. This model reduces the number of potential (feasible) solutions and enables to get closer to optimal fixture construction solutions from all three requirement standpoints - technical, environmental, and economic aspects.

3. METHODOLOGY

Detailed methodology of implementation of eco-design into fixture design process is shown in Fig. 3.

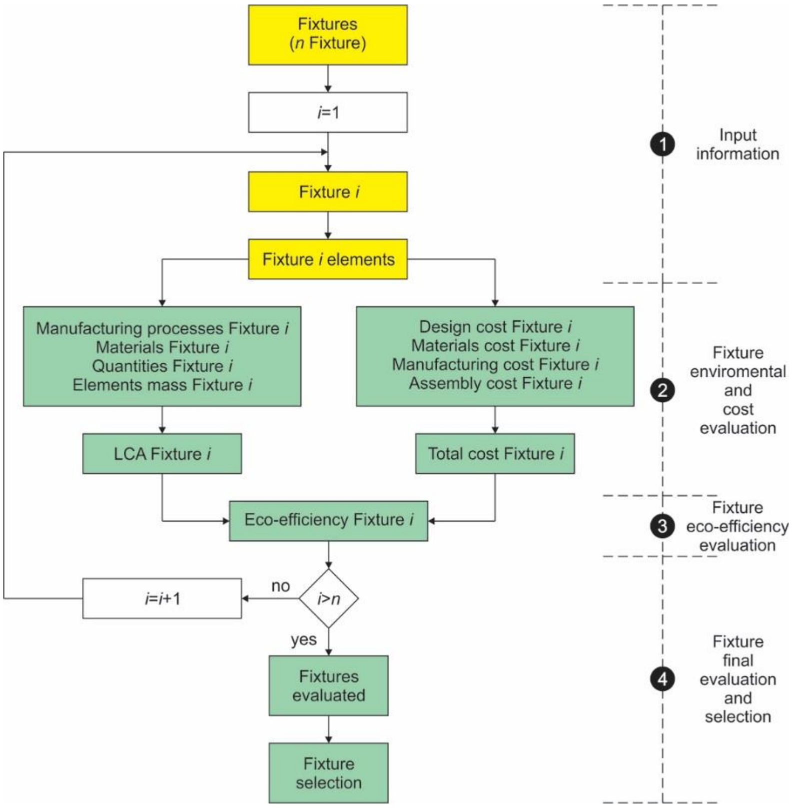


Figure 3: Methodology of implementation of eco-design.

Proposed fixture eco-design methodology is realized through the four levels (segments):

- level for input information,
- level for fixture environmental and cost evaluation,
- level for eco-efficiency evaluation,
- level for fixture final evaluation and selection.

For each fixture solution that fulfils technical requirements, construction and fixture elements are known. At the same time, these are the input information for the proposed methodology.

Input information can be grouped in: information related to environmental perspective of fixture element design (manufacturing processes, materials, quantities, and masses), and information related to economic perspective of fixture design (design fixture cost, material cost, manufacturing cost, and assembly cost).

In order to implement LCA in eco-design, for each fixture element manufacturing processes, materials, quantities, and masses have to be defined. Afterwards it is feasible to conduct LCA for each fixture construction. Aiming to connect each LCI result to the corresponding environmental impact, IMPACT 2002+ life cycle impact assessment (LCIA) method has been applied. IMPACT 2002+ LCIA method was selected because it provides calculation of endpoint results that will be used for calculation of eco-efficiency (EE). IMPACT 2002+ method enables midpoint and endpoint (damage) LCA approach. Results from the midpoint impact categories are located between the LCI results and the endpoint impact categories on the environmental impact pathway. There are fourteen midpoint impact categories in IMPACT 2002+ method: human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic eco-toxicity, terrestrial eco-toxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nitrification, land occupation, global warming, non-renewable energy, and mineral extraction. Midpoint impact categories are further allocated into one or more of the four endpoint impact categories:

human health, ecosystem quality, climate change, and resources. After normalization, four endpoint impact categories results are dimensionless, expressed in points (Pt), which present the average impact in a specific category caused by a person during one year in Europe. Since normalized endpoint impact category results have same unit, they can be weighted and aggregated into single score that presents the total environmental impact. The LCA is conducted to assess the environmental impacts and compare eco-design alternatives for the fixture. The total environmental impact is the sum of the endpoint impact category results from LCA.

Furthermore, it is possible to account all the fixture costs and to perform cost analysis. Cost analysis will provide insights into the economic aspects related to the fixture and will include the costs of design, material, manufacture, and assembly.

Individual costs are formed as:

- Fixture design cost implies designing costs of individual fixture elements and fixture construction. This cost is defined by the fixture designer.
- Material cost is obtained from the prices of materials spent for manufacturing of individual fixture elements. Material cost is equal to sum of individual fixture element cost. This is the cost of initial amount of material needed for blanks from which fixture elements are made of.
- Manufacturing cost is based on price of individual fixture elements manufacturing costs, i.e., as a sum of each elements manufacturing costs. Manufacturing cost is influenced by the applied manufacturing processes costs (milling, grinding, turning, drilling, carburizing, quenching, hardening, etc.).
- Assembly cost is based on cost of assembly, i.e. time needed for assembly of fixture construction.

The total fixture cost is the sum of all costs.

With the aim of combining the environmental impact and cost into a single indicator, eco-efficiency has been introduced. The eco-efficiency (EE) of the i^{th} evaluated fixture is calculated as the ratio between the total fixture cost (TFC) and total environmental impact (TEI):

$$EEi = TFCi \,/\, TEIi \tag{1}$$

Based on eco-efficiency parameters, fixtures can be mutually compared. Fixture designer has the choice to select one of several fixtures construction on the basis of environmental and/or economic criteria. It has to be noted that all potential fixture construction solutions have to fulfil the technical requirements because otherwise faulty product would be produced. Therefore, LCA and cost analysis can be performed only on fixture constructions that previously fulfilled the technical requirements.

4. RESULTS

4.1 Input information for fixture eco-design

Methodology shown in Fig. 3 is applied on four fixture types, namely F1, F2, F3, and F4. Shown fixture constructions are designed in previously developed system for fixture design [34]. All four fixture constructions fulfil the needed technical requirements.

All fixtures have been designed for complex geometry workpieces. The considered fixtures are displayed in Fig. 4. Fixtures have been designed for locating and clamping of identical workpieces considering the fulfilment of all the technical requirements. Workpiece locating for all the fixture constructions is managed on the inner (construction F1) or outer (constructions F2–F4) surfaces. Workpiece clamping is done from the outer side. Each fixture provides manufacturing within the required tolerance thresholds and geometrical specifications. Fixtures have been designed to provide manufacturing with a large number of cutting tools. In this way, significant improvements in accuracy, quality, and productivity are achieved. It has to be noted that all four fixture constructions fulfil the technical requirements, thus all of them can be used in manufacturing.

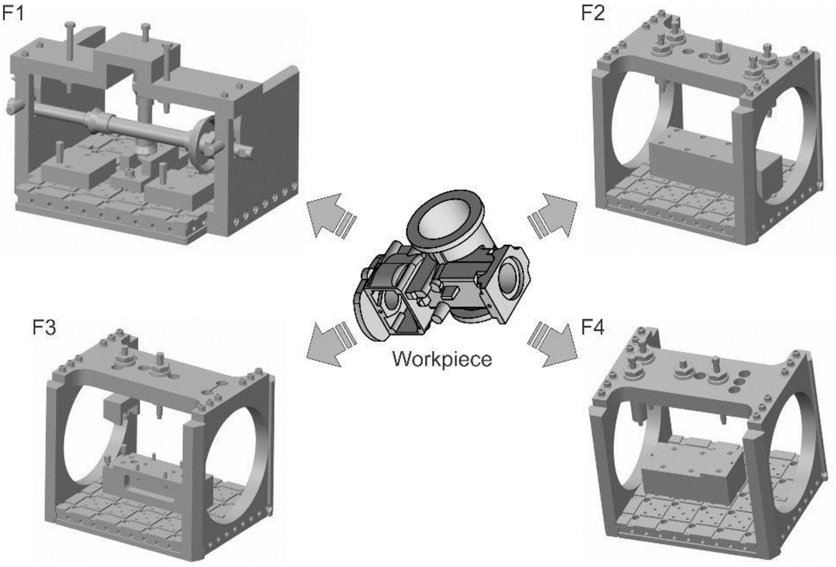
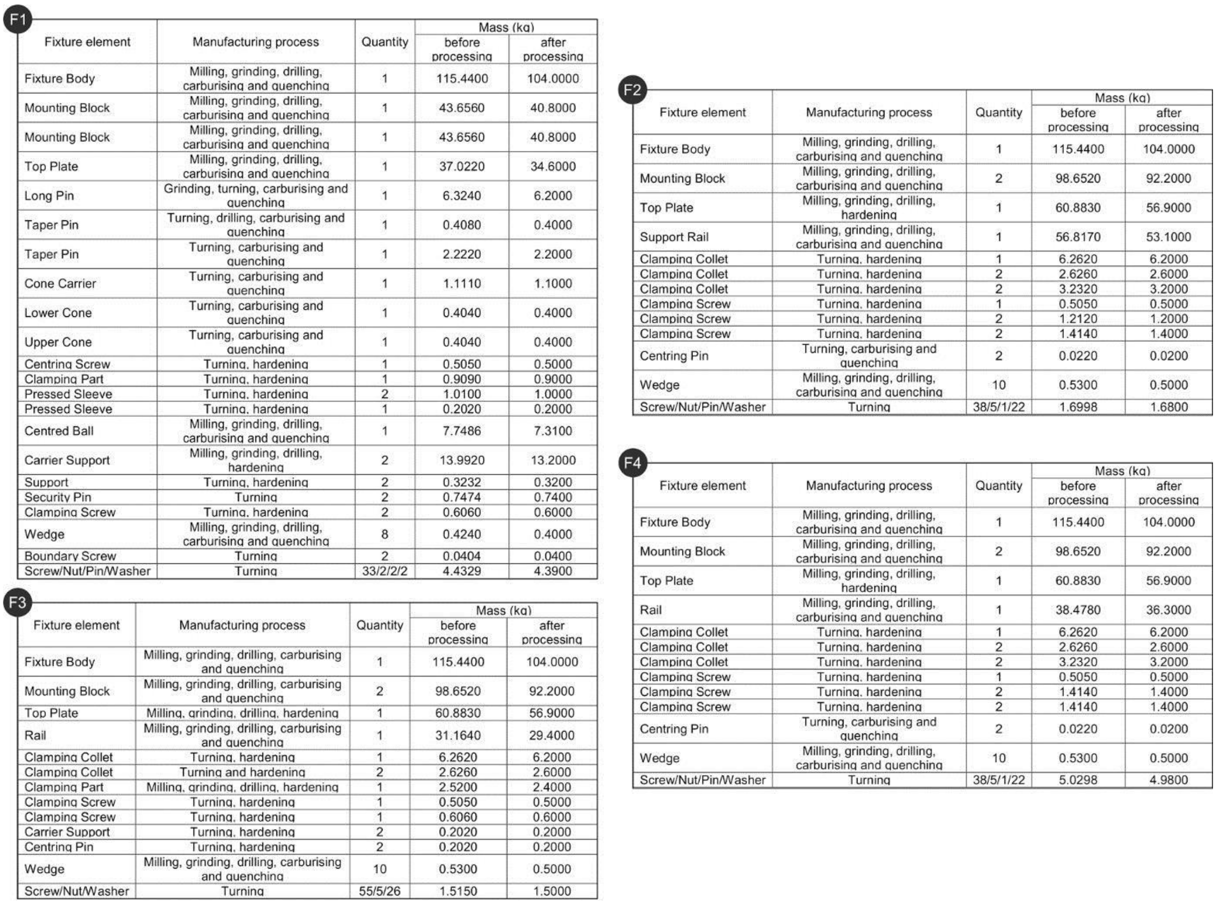


Figure 4: Workpiece and fixtures F1, F2, F3, and F4.

Fixture elements are defined for all four fixture constructions. For all the fixtures, and their elements, processes, materials, amounts, and masses have been defined (Fig. 5).



F1

Fixture element	Manufacturing process	Quantity	Mass (kg)	
			before processing	after processing
Fixture Body	Milling, grinding, drilling, carburising and quenching	1	115.4400	104.0000
Mounting Block	Milling, grinding, drilling, carburising and quenching	1	43.6560	40.8000
Mounting Block	Milling, grinding, drilling, carburising and quenching	1	43.6560	40.8000
Top Plate	Milling, grinding, drilling, carburising and quenching	1	37.0220	34.6000
Long Pin	Grinding, turning, carburising and quenching	1	6.3240	6.2000
Taper Pin	Turning, drilling, carburising and quenching	1	0.4080	0.4000
Taper Pin	Turning, carburising and quenching	1	2.2220	2.2000
Cone Carrier	Turning, carburising and quenching	1	1.1110	1.1000
Lower Cone	Turning, carburising and quenching	1	0.4040	0.4000
Upper Cone	Turning, carburising and quenching	1	0.4040	0.4000
Centring Screw	Turning, hardening	1	0.5050	0.5000
Clamping Part	Turning, hardening	1	0.9090	0.9000
Pressed Sleeve	Turning, hardening	2	1.0100	1.0000
Pressed Sleeve	Turning, hardening	1	0.2020	0.2000
Centred Ball	Milling, grinding, drilling, carburising and quenching	1	7.7486	7.3100
Carrier Support	Milling, grinding, drilling, hardening	2	13.9920	13.2000
Support	Turning, hardening	2	0.3232	0.3200
Security Pin	Turning	2	0.7474	0.7400
Clamping Screw	Turning, hardening	2	0.6060	0.6000
Wedge	Milling, grinding, drilling, carburising and quenching	8	0.4240	0.4000
Boundary Screw	Turning	2	0.0404	0.0400
Screw/Nut/Pin/Washer	Turning	33/2/2/2	4.4329	4.3900

F2

Fixture element	Manufacturing process	Quantity	Mass (kg)	
			before processing	after processing
Fixture Body	Milling, grinding, drilling, carburising and quenching	1	115.4400	104.0000
Mounting Block	Milling, grinding, drilling, carburising and quenching	2	98.6520	92.2000
Top Plate	Milling, grinding, drilling, hardening	1	60.8830	56.9000
Support Rail	Milling, grinding, drilling, carburising and quenching	1	56.8170	53.1000
Clamping Collet	Turning, hardening	1	6.2620	6.2000
Clamping Collet	Turning, hardening	2	2.6260	2.6000
Clamping Collet	Turning, hardening	2	3.2320	3.2000
Clamping Screw	Turning, hardening	1	0.5050	0.5000
Clamping Screw	Turning, hardening	2	1.2120	1.2000
Clamping Screw	Turning, hardening	2	1.4140	1.4000
Centring Pin	Turning, carburising and quenching	2	0.0220	0.0200
Wedge	Milling, grinding, drilling, carburising and quenching	10	0.5300	0.5000
Screw/Nut/Pin/Washer	Turning	38/5/1/22	1.6998	1.6800

F3

Fixture element	Manufacturing process	Quantity	Mass (kg)	
			before processing	after processing
Fixture Body	Milling, grinding, drilling, carburising and quenching	1	115.4400	104.0000
Mounting Block	Milling, grinding, drilling, carburising and quenching	2	98.6520	92.2000
Top Plate	Milling, grinding, drilling, hardening	1	60.8830	56.9000
Rail	Milling, grinding, drilling, carburising and quenching	1	31.1640	29.4000
Clamping Collet	Turning, hardening	1	6.2620	6.2000
Clamping Collet	Turning and hardening	2	2.6260	2.6000
Clamping Part	Milling, grinding, drilling, hardening	1	2.5200	2.4000
Clamping Screw	Turning, hardening	1	0.5050	0.5000
Clamping Screw	Turning, hardening	1	0.6060	0.6000
Carrier Support	Turning, hardening	2	0.2020	0.2000
Centring Pin	Turning, hardening	2	0.2020	0.2000
Wedge	Milling, grinding, drilling, carburising and quenching	10	0.5300	0.5000
Screw/Nut/Washer	Turning	55/5/26	1.5150	1.5000

F4

Fixture element	Manufacturing process	Quantity	Mass (kg)	
			before processing	after processing
Fixture Body	Milling, grinding, drilling, carburising and quenching	1	115.4400	104.0000
Mounting Block	Milling, grinding, drilling, carburising and quenching	2	98.6520	92.2000
Top Plate	Milling, grinding, drilling, hardening	1	60.8830	56.9000
Rail	Milling, grinding, drilling, carburising and quenching	1	38.4780	36.3000
Clamping Collet	Turning, hardening	1	6.2620	6.2000
Clamping Collet	Turning, hardening	2	2.6260	2.6000
Clamping Collet	Turning, hardening	2	3.2320	3.2000
Clamping Screw	Turning, hardening	1	0.5050	0.5000
Clamping Screw	Turning, hardening	2	1.4140	1.4000
Clamping Screw	Turning, hardening	2	1.4140	1.4000
Centring Pin	Turning, carburising and quenching	2	0.0220	0.0200
Wedge	Milling, grinding, drilling, carburising and quenching	10	0.5300	0.5000
Screw/Nut/Pin/Washer	Turning	38/5/1/22	5.0298	4.9800

Figure 5: Elements of fixtures F1, F2, F3, and F4.

4.2 Fixture environmental and cost evaluation

Based on the previously defined input information, environmental and cost evaluation has been performed for all four fixtures.

Table I: Life cycle inventory for four fixture types.

Materials and manufacturing processes	Unit	Process in Ecoinvent LCI database	Notes	Fixture type			
				F1	F2	F3	F4
Steel	kg	Steel, low-alloyed, at plant/RER S	Mass of finished fixture element	260.50	323.50	297.20	310.20
Milling	kg	Milling, steel, average/RER S	4–8 % of the material is removed by milling depending on the part size	14.97	18.45	17.07	17.25
Grinding	kg	–	Inventory obtained from Murray et al. (2012). 1 % of material is removed by grinding	3.51	4.11	3.89	3.94
Turning	kg	Turning, steel, CNC, average/RER S	1 % of material is removed by turning	0.19	0.17	0.12	0.20
Drilling	kg	Drilling, CNC, steel/RER S	3 % of material is removed by drilling	2.42	3.07	2.83	2.90
Carburizing and quenching	kWh	Electricity, low voltage, production CS, at grid/CS S	0.3333 kWh of electricity is consumed for treatment of 1 kg of material	79.53	83.27	75.36	77.67
Hardening	kWh	Electricity, low voltage, production CS, at grid/CS S	0.14 kWh of electricity is consumed for treatment of 1 kg of material	2.34	10.08	9.74	10.11
Collection of chips	kg	Iron scrap, at plant/RER S	The process “Iron scrap, at plant/RER S” is used to include the environmental burdens associated with collection of chips. The amount is equal to the mass of all material removed by the cutting processes.	21.09	25.79	23.91	24.29
Recycling of chips	kg	Pig iron, at plant/GLO S	The process “Pig iron, at plant/GLO S” is used as an avoided product in LCA in order to account for the environmental benefits from recycling of chips. The amount is equal to the mass of all material removed by the cutting processes.	21.09	25.79	23.91	24.29

The purpose of the LCA study is to compare the four fixture types and to assess their environmental impacts. Thus, attributional LCA modelling is applied. The functional unit is one fixture that has to secure the locating and clamping of the workpiece and to allow manufacturing according to previously defined technical requirements. The system boundaries are cradle-to-gate type and include only the extraction of resources from nature and the manufacturing stages of the fixture's life cycle. Life span is difficult to predict or determine because fixture and its elements can be reused numerous times. Therefore, use phase is omitted from system boundaries. The IMPACT 2002 life cycle impact assessment (LCIA) method and the Ecoinvent 3.0 LCI database in SimaPro 8 were used to model the LCA.

The production of fixtures consists of conventional CNC manufacturing processes such as milling, grinding, turning, and drilling but also thermal treatment by carburization, quenching, and hardening. The LCI for the production of four fixture types is provided in Table I. Foreground data are obtained from the designer and manufacturer of fixtures, while the background data are obtained from Ecoinvent LCI database. Most of the processes are obtained from the Ecoinvent 3.0 LCI database, except for the grinding process, which was modelled according to the inventory provided in research by [9].

Input in LCIA is the information from LCI presented in table I. Output from LCIA are results from the IMPACT 2002+ endpoint LCIA method expressed through the four endpoint impact categories: human health, ecosystem quality, climate change, and resources. LCA results for fixture types F1–F4 are shown in Figs. 6 and 7.

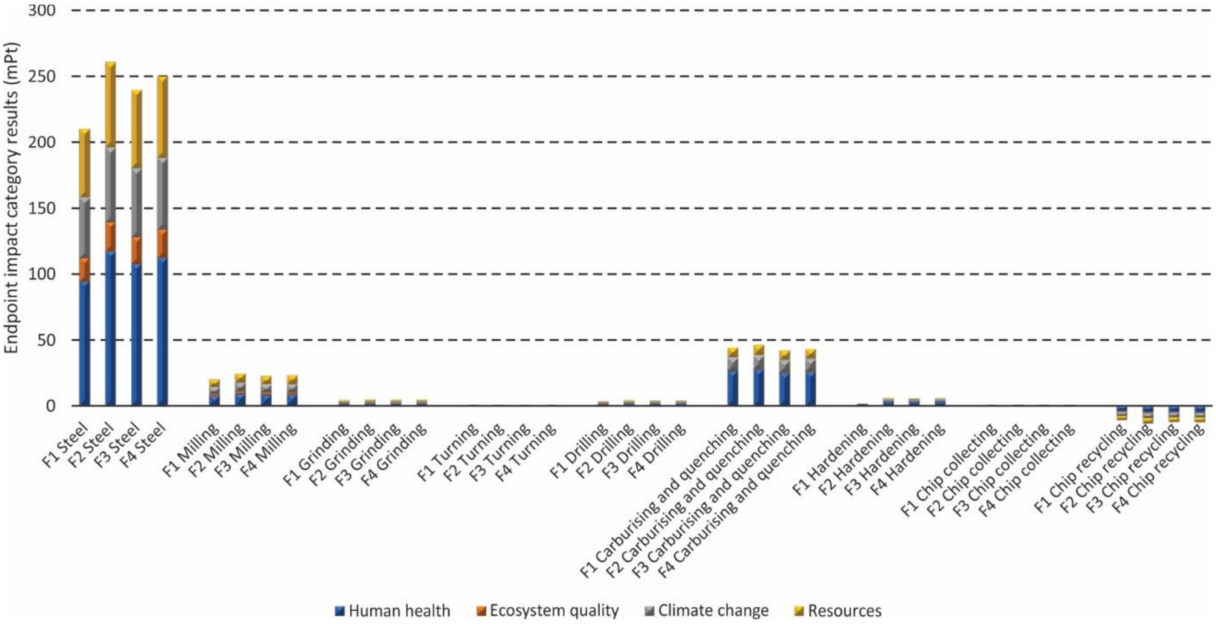


Figure 6: Comparison of LCA results for the manufacturing processes of four fixture types.

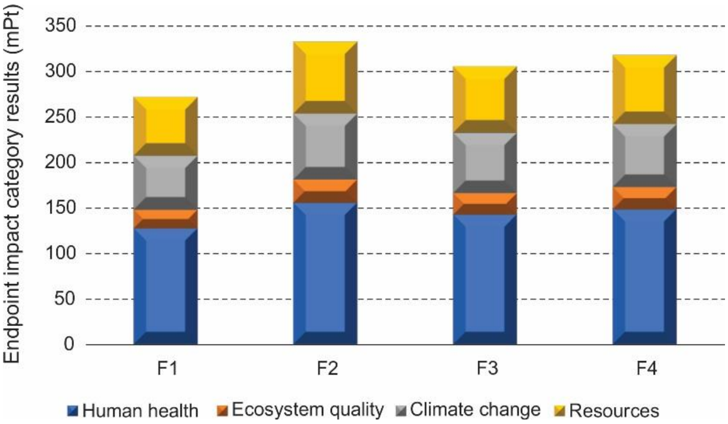


Figure 7: Comparison of LCA results for four fixture types.

Fixture cost evaluation implies defining the total costs for all four fixture constructions. The total fixture costs are divided into the costs of design, materials, manufacturing, and assembly. Table II shows the fixture costs.

Table II: Fixture costs.

Cost (EUR)	**Fixture Type**			
	F1	**F2**	**F3**	**F4**
Design cost	630	460	550	530
Material cost	534	340	412	387
Manufacturing cost	2886	1870	2244	2117
Assembly cost	100	70	80	80
Total fixture cost	4150	2740	3286	3114

4.3 Fixture eco-efficiency evaluation

According to the previously obtained total environmental impact and total fixture cost, the eco-efficiency parameters are provided in Table III. Damage category, human health, ecosystem quality, climate change, resources, and total environmental impact are obtained from LCA (Fig. 7). Total fixture cost is obtained from cost analysis. Eco-efficiency of each fixture is calculated as a ratio of total fixture cost and total environmental impact. Total environmental impact is calculated as *TEI*/*TEImin*, while the total fixture cost ratio as *TFC*/*TFCmin*.

Table III: Calculation of eco-efficiency parameters.

Damage category	**Unit**	**F1**	**F2**	**F3**	**F4**
Human health	mPt	127.72	155.74	142.91	148.63
Ecosystem quality	mPt	20.86	25.79	23.70	24.67
Climate change	mPt	59.08	72.32	66.38	69.05
Resources	mPt	64.34	79.03	72.59	75.52
Total environmental impact *TEI*	mPt	272.00	332.87	305.59	317.87
Total fixture cost *TFC*	EUR	4150.00	2740.00	3286.00	3114.00
Eco-efficiency *EE*	/	15.26	8.23	10.75	9.80
Total environmental impact ratio *TEI*/*TEImin*	/	1.00	1.22	1.12	1.17
Total fixture cost ratio *TFC*/*TFCmin*	/	1.00	0.66	0.79	0.75

Based on the calculated eco-efficiency parameters from Table III, the relationship between the total environmental impact and total fixture cost ratios is illustrated in Fig. 8.

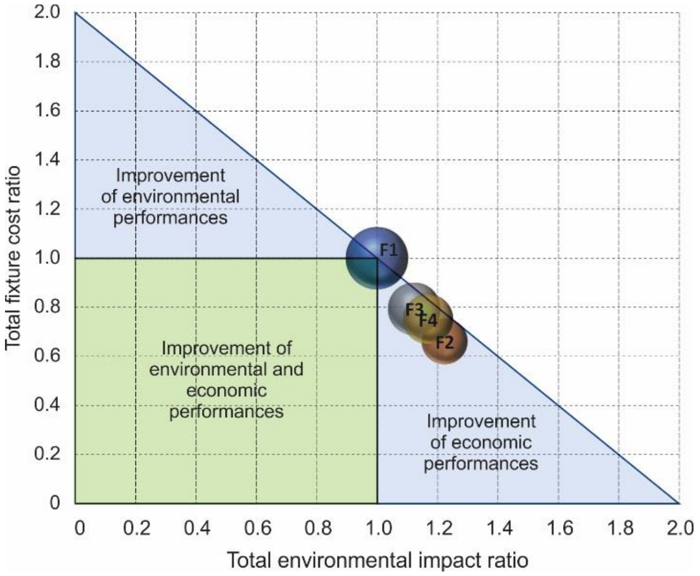


Figure 8: Relationship between the total environmental impact and total fixture cost ratios.

4.4 Fixture final evaluation and selection

Eco-efficiency provides a good representation of the ratio between the fixture cost and the environmental impact. If fixture construction would have simultaneously least negative impact on the environment and with lowest cost, then this fixture construction would have best eco-efficiency.

The results in Table III show that fixture F1 has the best eco-efficiency (*EE*1=15.26), followed by fixtures F3 (*EE*3 = 10.75) and F4 (*EE*4 = 9.80), while fixture F2 has the worst eco-efficiency (*EE*2 = 8.23). Therefore, fixture F1 is taken as the default having the best eco-efficiency, while other fixtures have been compared with F1 on the basis of costs and environmental impact in order to perform a graphical interpretation (Fig. 8). Although fixtures F2-F4 have lower eco-efficiency, they also have lower costs, resulting in improvement of their economic performances.

Fixture constructions eco-efficiency indicates possibility of opposed results from environmental and economic aspects. Therefore, fixture construction with best environmental properties has largest costs. In these situations, fixture designer has to decide which construction should be selected depending on the criteria that are more important in specific case. For example, if fixture designer is limited with funding he will choose cheaper fixture construction, while if environmental impact is more important because of legislative requirements, then he will choose construction with less negative impact on the environment. Compromise solution between two opposite cases is also available.

5. DISCUSSION

The largest total environmental impact comes from the consumption of steel (210-260 mPt) in the fixture manufacturing process (Fig. 6). The total environmental impact from steel production exceeds all the impacts originating from the manufacturing processes combined together (milling, grinding, turning, drilling, carburizing and quenching, hardening, and chip recycling contribute up to 72 mPt). The second largest total environmental impact comes from carburizing and quenching (up to 46 mPt), where a large amount of electricity is consumed. Here it has to be pointed out that the Serbian electricity mix has a high environmental impact because it consists mainly of burning of lignite in power plants (66 %) and hydropower (32 %). If a different country’s electricity mix were used, with cleaner electricity sources, the total environmental impact of carburizing and quenching could be significantly lower. The positive environmental impact comes from chip recycling, where pig iron is modelled as an avoided product in LCA.

When the four types of fixtures are compared with one another (Fig. 7), the second fixture (F2) has the largest total environmental impact, followed by the fourth (F4) and third (F3), while the first fixture (F1) has the lowest. It can be concluded that the total environmental loading is heavily impacted by the amount of steel used, and the environmental loading is proportional to the steel mass. Accordingly, the second fixture (F2) is the heaviest with a mass of 323.5 kg (Table I) and F2 has the largest total environmental impact of 333 mPt. The fourth fixture (F4) has a mass of 310.2 kg and a total environmental loading of 318 mPt, the third (F3) has a mass of 297.2 kg and a total environmental loading of 306 mPt, and the first (F1) is the lightest, with a mass of 260.5 kg and accordingly the lowest total environmental loading of 272 mPt.

The total fixture costs are equal to the sum of the costs of design, material, manufacturing, and assembly. Depending on the fixture type and based on the data from Table II, the following conclusions can be drawn:

- the cost of design is 15-17 % of the total fixture costs,

- the cost of material is 12-13 % of the total fixture costs,
- the cost of manufacturing is 68-70 % of the total fixture costs,
- the cost of assembly is 2-3 % of the total fixture costs.

In contrast to the idea that the environmental loading is proportional to costs, in this case the fixture costs are almost inversely proportional to the environmental impacts. Namely, the most expensive fixture construction (F1, with a total fixture cost of 4150 euros) has the lowest total environmental loading of 272 mPt, whereas the least expensive fixture construction (F2, with a total fixture cost of 2740 euros) has the highest total environmental loading of 333 mPt. Fixture F3 is the fixture with the second highest environmental loading of 306 mPt and also the second most expensive fixture, with a total cost of 3286 euros. The fourth fixture (F4) has a total environmental loading almost the same as that of fixture F2 and a cost of 3114 euros. Investment economies can be achieved if fixtures are disassembled after use and their elements reused in other fixtures. After the use phase, fixtures are returned to the assembly department, where they are disassembled and stored in previously determined places. New fixtures are assembled from disassembled fixtures. This circular process ensures the rational use of fixture elements. In this way, costs and negative impacts on the environment are reduced.

6. CONCLUSION

Design is the life cycle phase where decision making significantly impacts and determines other life cycle phases. Therefore, the use of eco-design tools is highly recommended in order to develop optimal products. Fixture eco-design in modern manufacturing systems tends to achieve a sustainable fixture life cycle.

Obtained results from the new developed model show that it is possible to implement environmental and cost analysis in fixture design process and to enable comparative analysis of fixture constructions by three standpoints, technical, environmental and economic. Developed model can be implemented in all previous research in field of fixture design considering that input information's are output from previous methods and systems. Eco-efficiency parameters provide fixture construction comparability and selection of best alternative for defined requirements.

Obtained results show that the environmental impact is closely related to material from which fixture is made and that the impact on human health is largest. This indicates that with selection of suitable materials for fixture elements negative environmental impact can be reduced. Furthermore, the fact that cannot be neglected is that steel is the material dominantly used for manufacturing of majority of fixture elements primarily because of its good mechanical and physical properties, as well as affordable price, good processing abilities, and other positive properties. Some manufacturing processes such as carburizing and quenching consume large amounts of electricity. Aiming to reduce electricity consumption these processes can be substituted with alternative processes that contribute to increase of fixture element's surface hardness, such as burnishing, cementation, etc. Fixture manufacturing costs related to manufacturing processes are the dominant ones (up to 70 %). Careful selection of alternative manufacturing processes can improve environmental footprint and reduce costs. If further research tends to evaluate changes in environmental impacts due to use of alternative processes in fixture manufacturing, consequential LCA modelling is recommended.

Future research should focus on further analysis of the exploitation and end-of-life phases. This could include assessment of other fixture aspects such as reliability, user-friendliness, and operational safety.

REFERENCES

[1] Kalpakjian, S.; Schmid, R. S. (2014). *Manufacturing Engineering and Technology*, 7th edition, Pearson, Singapore

[2] Groover, P. M. (2010). *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*, 4th edition, John Wiley & Sons, Hoboken

[3] Stark, R.; Seliger, G.; Bonvoisin, J. (2017). *Sustainable Manufacturing: Challenges, Solutions and Implementation Perspectives*, Springer, Cham

[4] Rajemi, M. F.; Mativenga, P. T.; Aramcharoen, A. (2010). Sustainable machining: selection of optimum turning conditions based on minimum energy considerations, *Journal of Cleaner Production*, Vol. 18, No. 10-11, 1059-1065, doi:10.1016/j.jclepro.2010.01.025

[5] Bhushan, R. K. (2013). Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites, *Journal of Cleaner Production*, Vol. 39, 242-254, doi:10.1016/j.jclepro.2012.08.008

[6] Gaha, R.; Yannou, B.; Benamara, A. (2014). A new eco-design approach on CAD systems, *International Journal of Precision Engineering and Manufacturing*, Vol. 15, No. 7, 1443-1451, doi:10.1007/s12541-014-0489-4

[7] Aramcharoen, A.; Mativenga, P. T. (2014). Critical factors in energy demand modelling for CNC milling and impact of toolpath strategy, *Journal of Cleaner Production*, Vol. 78, 63-74, doi:10.1016/j.jclepro.2014.04.065

[8] Hassine, H.; Barkallah, M.; Bellacicco, A.; Louati, J.; Riviere, A.; Haddar, M. (2015). Multi objective optimization for sustainable manufacturing, application in turning, *International Journal of Simulation Modelling*, Vol. 14, No. 1, 98-109, doi:10.2507/IJSIMM14(1)9.292

[9] Murray, V. R.; Zhao, F.; Sutherland, J. W. (2012). Life cycle analysis of grinding: a case study of non-cylindrical computer numerical control grinding via a unit-process life cycle inventory approach, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 226, No. 10, 1604-1611, doi:10.1177/0954405412454102

[10] Palčič, I.; Pons, M.; Bikfalvi, A.; Llach, J.; Buchmeister, B. (2013). Analysing energy and material saving technologies' adoption and adopters, *Strojniski vestnik – Journal of Mechanical Engineering*, Vol. 59, No. 6, 409-419, doi:10.5545/sv-jme.2012.830

[11] Winter, M.; Li, W.; Kara, S.; Herrmann, C. (2014). Stepwise approach to reduce the costs and environmental impacts of grinding processes, *International Journal of Advanced Manufacturing Technology*, Vol. 71, No. 5-8, 919-931, doi:10.1007/s00170-013-5524-6

[12] Winter, M.; Ibbotson, S.; Kara, S.; Herrmann, C. (2015). Life cycle assessment of cubic boron nitride grinding wheels, *Journal of Cleaner Production*, Vol. 107, 707-721, doi:10.1016/j.jclepro.2015.05.088

[13] Silva, D. A. L.; Filleti, R. A. P.; Christoforo, A. L.; Silva, E. J.; Ometto, A. R. (2015). Application of Life Cycle Assessment (LCA) and Design of Experiments (DOE) to the monitoring and control of a grinding process, *Procedia CIRP*, Vol. 29, 508-513, doi:10.1016/j.procir.2015.01.037

[14] Liu, Z. Y.; Guo, Y. B.; Sealy, M. P.; Liu, Z. Q. (2016). Energy consumption and process sustainability of hard milling with tool wear progression, *Journal of Materials Processing Technology*, Vol. 229, 305-312, doi:10.1016/j.jmatprotec.2015.09.032

[15] Deng, Z.; Lv, L.; Li, S.; Wan, L.; Liu, W.; Yan, C.; Zhang, H. (2016). Study on the model of high efficiency and low carbon for grinding parameters optimization and its application, *Journal of Cleaner Production*, Vol. 137, 1672-1681, doi:10.1016/j.jclepro.2016.03.022

[16] Li, B.; Cao, H.; Yan, J.; Jafar, S. (2017). A life cycle approach to characterizing carbon efficiency of cutting tools, *International Journal of Advanced Manufacturing Technology*, Vol. 93, No. 9-12, 3347-3355, doi:10.1007/s00170-017-0728-9

[17] Bagaber, S. A.; Yusoff, A. R. (2017). Multi-objective optimization of cutting parameters to minimize power consumption in dry turning of stainless steel 316, *Journal of Cleaner Production*, Vol. 157, 30-46, doi:10.1016/j.jclepro.2017.03.231

[18] Zhang, C.; Liu, C.; Zhao, X. (2017). Optimization control method for carbon footprint of machining process, *International Journal of Advanced Manufacturing Technology*, Vol. 92, No. 5-8, 1601-1607, doi:10.1007/s00170-017-0241-1

[19] Filleti, R. A. P.; Silva, D. A. L.; da Silva, E. J.; Ometto, A. R. (2017). Productive and environmental performance indicators analysis by a combined LCA hybrid model and real-time manufacturing process monitoring: A grinding unit process application, *Journal of Cleaner Production*, Vol. 161, 510-523, doi:10.1016/j.jclepro.2017.05.158

[20] Li, L.; Li, C.; Tang, Y.; Li, L. (2017). An integrated approach of process planning and cutting parameter optimization for energy-aware CNC machining, *Journal of Cleaner Production*, Vol. 162, 458-473, doi:10.1016/j.jclepro.2017.06.034

[21] Chen, Y.; Chen, X.; Xu, X.; Yu, G. (2018). Effect of energy consumption in the contact zone on machining condition optimization in precision surface grinding, *Strojniski vestnik – Journal of Mechanical Engineering*, Vol. 64, No. 4, 233-244, doi:10.5545/sv-jme.2017.4995

[22] Liu, Z. Y.; Li, C.; Fang, X. Y.; Guo, Y. B. (2018). Cumulative energy demand and environmental impact in sustainable machining of Inconel superalloy, *Journal of Cleaner Production*, Vol. 181, 329-336, doi:10.1016/j.jclepro.2018.01.251

[23] Chiu, M. C.; Chu, C. H. (2012). Review of sustainable product design from life cycle perspectives, *International Journal of Precision Engineering and Manufacturing*, Vol. 13, No. 7, 1259-1272, doi:10.1007/s12541-012-0169-1

[24] Peng, T.; Xu, X. (2014). Energy-efficient machining systems: a critical review, *International Journal of Advanced Manufacturing Technology*, Vol. 72, No. 9-12, 1389-1406, doi:10.1007/s00170-014-5756-0

[25] Zhou, L.; Li, J.; Li, F.; Meng, Q.; Li, J.; Xu, X. (2016). Energy consumption model and energy efficiency of machine tools: a comprehensive literature review, *Journal of Cleaner Production*, Vol. 112, No. 5, 3721-3734, doi:10.1016/j.jclepro.2015.05.093

[26] Hussain, S.; Jahanzaib, M. (2018). Sustainable manufacturing – An overview and a conceptual framework for continuous transformation and competitiveness, *Advances in Production Engineering & Management*, Vol. 13, No. 3, 237-253, doi:10.14743/apem2018.3.287

[27] Vukelic, D.; Zuperl, U.; Hodolic, J. (2009). Complex system for fixture selection, modification, and design, *International Journal of Advanced Manufacturing Technology*, Vol. 45, No. 7-8, 731-748, doi:10.1007/s00170-009-2014-y

[28] Wang, H.; Rong, Y. K.; Li, H.; Shaun, P. (2010). Computer aided fixture design: recent research and trends, *Computer-Aided Design*, Vol. 42, No. 12, 1085-1094, doi:10.1016/j.cad.2010.07.003

[29] Bi, Z. M.; Zhang, W. J. (2001). Flexible fixture design and automation: review, issues and future directions, *International Journal of Production Research*, Vol. 39, No. 13, 2867-2894, doi:10.1080/00207540110054579

[30] Matejic, M.; Tadic, B.; Lazarevic, M.; Misic, M.; Vukelic, D. (2018). Modelling and simulation of a novel modular fixture for a flexible manufacturing system, *International Journal of Simulation Modelling*, Vol. 17, No. 1, 18-29, doi:10.2507/IJSIMM17(1)407

[31] Boyle, I.; Rong, Y.; Brown, D. C. (2011). A review and analysis of current computer-aided fixture design approaches, *Robotics and Computer-Integrated Manufacturing*, Vol. 27, No. 1, 1-12, doi:10.1016/j.rcim.2010.05.008

[32] Gameros, A.; Lowth, S.; Axinte, D.; Nagy-Sochacki, A.; Craig, O.; Siller, H. R. (2017). State-of-the-art in fixture systems for the manufacture and assembly of rigid components: A review, *International Journal of Machine Tools and Manufacture*, Vol. 123, 1-21, doi:10.1016/j.ijmachtools.2017.07.004

[33] Vasundara, M.; Padmanaban, K. P. (2014). Recent developments on machining fixture layout design, analysis, and optimization using finite element method and evolutionary techniques, *International Journal of Advanced Manufacturing Technology*, Vol. 70, No. 1-4, 79-96, doi:10.1007/s00170-013-5249-6

[34] Vukelic, D.; Simunovic, G.; Tadic, B.; Buchmeister, B.; Saric, T.; Simeunovic, N. (2016). Intelligent design and optimization of machining fixtures, *Technical Gazette*, Vol. 23, No. 5, 1325-1334, doi:10.17559/TV-20150908142130