COMPUTER-AIDED DESIGN & APPLICATIONS, 2018
VOL. 15, NO. 5, 734–746
https://doi.org/10.1080/16864360.2018.1441240

CAD feature recognition as a means to prevent ergonomics issues during manual assembly tasks

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ABSTRACT
Feature-based modeling and feature recognition algorithm are state of the art technologies, mainly used to favor the integration and exchange of data between design and manufacturing phases. This paper aims to investigate the possibility to extend the use of the feature recognition as a means for the prevention of ergonomics issues during the manual assembly phase, such as Work-related Musculo-Skeletal Disorders (WMSDs). Starting from the features analysis of a 3D product model, the proposed five steps method allows preventively identifying potential ergonomics issues. The main novelty of this study is related to the correlation between design tools, product virtual representations (e.g. 3D models), assembly and ergonomics aspects. Results obtained with two case studies, a cooker hood and a tool-holder carousel, confirm the usefulness of the proposed method in helping designers to prevent potential ergonomics issues for operators involved in the assembly phase.

KEYWORDS
Feature recognition; Virtual product model; Manual assembly; Ergonomics; Work-related Musculoskeletal Disorders

1. Introduction

In the last three decades, feature-based modeling approaches and feature-based computer-aided systems (CAx) emerged as state of the art technologies in the field of product modeling [9]. Relevant research efforts in this topic have been focused on the development of algorithms, methods and tools for the automatic recognition of features (AFR) from 3D models [1][16]. They mainly concern the development of procedures for the efficient extraction of relevant entities (i.e. features) from solid models.

This paper intends to extend the use of feature recognition algorithms as a means to improve the product assemblability and to prevent ergonomics issues associated to the manual assembly tasks. According to the latest international reports on health workers' and employees' conditions, the Work-related Musculo-Skeletal Disorders (WMSDs) are becoming more frequent in the last 30 years than in the past [22]. The prevention of WMSDs is an important activity for different reasons: (i) to maintain young workers' capability and optimal health conditions, (ii) to ensure older workers a healthy working life until their retirement, (iii) to avoid workers' substitution when absent for WMSD disturbs, (iv) to avoid workers' reallocation when affected by WMSDs, and (v) to avoid workers' complaints. A healthy workforce is an important prerequisite for industries to be competitive and to sustain an economic recovery [8].

Although advanced technologies have been implemented in assembly and manufacturing environments, such as robotics and automation systems, work diseases still remain an important issue. Manual assembly lines and workstations are the main cause of exposure to the upper limbs overload. The exposure of workers to the risk essentially depends on two principal aspects: (i) the product design and (ii) the workstation layout. Currently, the standard practice is to manage ergonomics aspects through the correct configuration and set up of the assembly line before the production starts, or, in the worst scenario, through the modification of assembly lines after the occurrence of one or more illness cases. It is clear that those ones are only corrective actions aiming to minimize the cost impact for the company without solving the root problem [10].

In this context, the main objective of this study is to define a method for managing physical risk factors during the product design and assembly planning processes. The step beyond the state of the art is the integration of design tools, product virtual representations (e.g. 3D models), assembly and ergonomics aspects. Starting from the features analysis of a 3D product model and thanks to some additional information about the

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assembly process (assembly plan, needed tools, etc.), the proposed method allows the preventive identification of potential ergonomics issues, thus facilitating the implementation of corrective actions during the design phase.

The paper is structured as follow: after a review of the state of the art in the context of feature recognition, design for assembly approaches and ergonomics (§2), the proposed method is described including the workflow and the metrics used for the assessment (§3). Two different products, a wall-mounted cooker hood and a tool-holder carousel of a CNC machine tool, are analyzed as case studies to validate the proposed approach (§4). Obtained results, limitations and future perspectives are discussed in the conclusions section (§5).

2. Research background

Feature recognition algorithms seek to recognize aggregates of entities with a clear design meaning, such as pockets, holes, fillets, etc., from the B-Rep geometry. In particular, recognition can be divided in: (i) graph-based approaches, (ii) volumetric decomposition approaches, and (iii) hint-based approaches [18][11][19]. The geometry formulation is generally not linked to a particular modeling strategy and it is read from standard formats (STEP, Acis, Parasolid). This choice is justified by the intrinsic difference between design and manufacturing features, which discourage using native feature commands of mechanical CAD systems, due to user dependent modeling strategies [15].

Many researchers employ the topological relationships of adjacent entities for the recognition of features, such as face adjacency graph or attributed adjacency graph. Indeed, many studies focus on the recognition and simplification of fillets and chamfers in order to lower the complexity of the volume patterns [23]. However, hint-based geometric reasoning has shown a better level of flexibility. The hint is a rule that expresses the trace of a searched pattern in the solid geometry. By expressing hints closer to the application domain, for instance ergonomics evaluations, it is possible to derive features which exhibit a clear meaning in the contexts they are used. Most of the feature recognition applications focus on the machining domain [18] and are not sufficient in the context of ergonomics evaluations. Some authors have discussed the possibility to associate feature types with manufacturing processes to support the process and assembly planning [21]. In particular, several research studies focus on how to efficiently extract information contained in Computer-Aided Design (CAD) models and reuse it in Computer-Aided Manufacturing (CAM) applications or in Computer-Aided Process Planning (CAPP) systems [11][7].

Assembly operations requires dealing with multiple parts and the spatial relations among them. Geometrical analysis cannot be limited to single components, but it requires additional information that is implicitly encoded in the assembly CAD models (e.g. relationships, joint constraints, etc.). For instance, in [13] the authors focus on the identification of regular patterns formed by repeated elements in an assembly, for automatic retrieval of models from vaults. In the context of ergonomics evaluations, such approach can provide useful information on the required assembly tasks. However, none of the abovementioned studies investigated the possibility to correlate product features, extracted from the virtual models, with ergonomics related aspects, as the prevention of WMSDs.

Concerning ergonomic aspects of the manual assembly process, existing ergonomic guidelines and studies gives suggestions on how to improve the workplace design and make the assembly task as ergonomically adequate as possible, by implementing organizational, structural and informative measures. Ergonomics principles are generally applied during the assembly line management without any prediction of physical risks related to the product features [10]. Workstation design and assembly line layout are the main topics considered in the field of occupational ergonomics associated to product assembly [5][20][14].

From the engineering design point of view, different methodologies and tools have been developed in order to maximize the product assembly performance. One of the most common approach is the Design for Assembly (DfA), which gives to designers a structured procedure and guidance to develop products to favour the assembly process [3]. The main aim of DfA methods is to identify design solutions for reducing the most critical tasks in terms of assembly time and cost. However, the application of traditional DfA methods does not generally lead to the improvement of ergonomics aspects of the assembly process.

Many studies focus on the simulation of ergonomics parameters by using virtual and simulation tools (e.g. kinematic analysis tools, virtual and augmented reality - VR/AR, etc.) to predict risky assembly tasks [2][4]. Commercial CAD tools provide extensions/plug-ins able to assess the ergonomics (e.g. JACK by Siemens, Manikin extension for CREO by PTC, Human Builder environment available in CATIA by Dassault Systèmes, etc.). These tools are useful in the investigation of ergonomics aspects and they are currently used for two main aims: (i) the end-user oriented design of assembled products, and (ii) the workstation design/redesign. In both cases, those tools are based on general anthropometric parameters and human factors. They do not consider detailed aspects of the component design and how geometry is related to manual assembly tasks. This is a technical limitation of these tools. In addition, the analysis of each assembly task for a complex product is a time-consuming activity.

An interesting integration between the DfA approach and the ergonomics aspects is proposed by Do Amaral and Menegon [6]. Results of this integration highlight the opportunity to prevent WMSDs before the assembly line is set up. However, this is only a preliminary and theoretical study, which does not give a structured procedure on how product features can be effectively used in real design contexts to improve the assembly process and the related ergonomics aspects.

The following conclusions can be derived from the presented critical review of the state of the art about feature recognition, assembly process ergonomics and design for assembly:

- Product features, recognized from virtual representations (i.e. CAD models) are generally used to integrate design and manufacturing phases, but ergonomics aspects are not considered;
- Ergonomics aspects are considered only during the assembly line design and management, by implementing remedial actions to solve specific issues (e.g., awkward postures of operators);
- DfA methods do not generally consider ergonomics.

This study aims to overcome these lacks by proposing a useful integration between product features, design for assembly and ergonomics.

3. Method

The concurrent analysis of the manual assembly tasks, working equipment and product features may help designers to assess ergonomics risks during the product development process. The final aim is to prevent possible physical risks for operators involved in the manual assembly of products (e.g. WMSDs). The framework of the proposed method is depicted in Fig. 1. The approach is characterized by five steps and they are described in detail in the next sub-sections.

3.1. 1st step: analysis of the manual assembly plan and production schedule

The starting point of the proposed method is represented by the analysis of the assembly plan, the production schedule, and the documents available during the product development process (i.e. embodiment and detail design phase). The analysis of project documents permits the identification of the assembly tasks involved in the overall assembly plan. Each assembly task is characterized in terms of:

- items to assemble;
- liaison types, e.g. screws, bolts, snap-fits, electric connections;
- assembly time needed to complete the task;
- frequency (for repetitive tasks);
- recovery time between a task and the successive one;
- necessary assembly tools to complete the task;
- necessary assembly equipment.

The mentioned data is used in the subsequent steps to perform the evaluation of ergonomics risks.

3.2. 2nd step: analysis of the product virtual model and recognition of relevant product features

After the analysis of the assembly plan and assembly tasks, the current configuration of the 3D product virtual

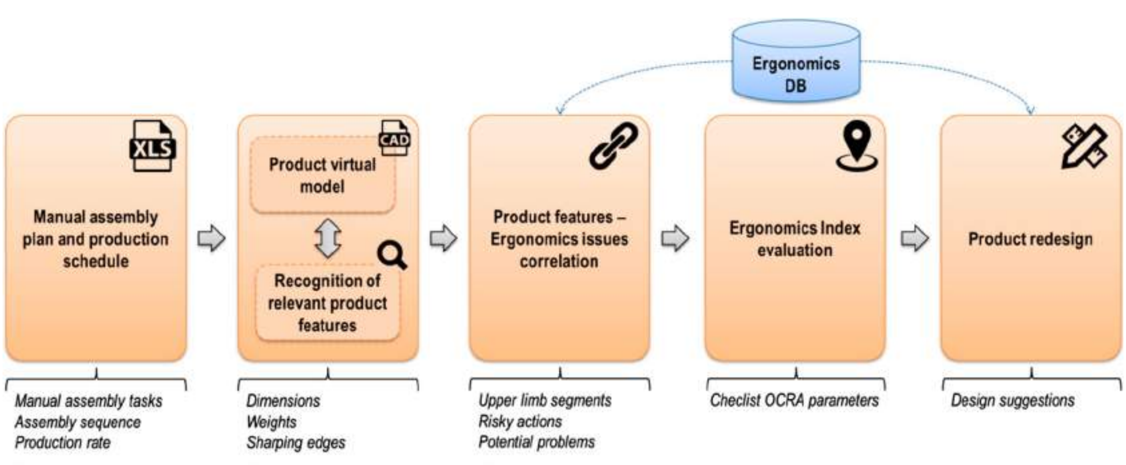


Figure 1. Workflow of the proposed method.

Table 1. Classification of the upper limb awkward postures and associated risk actions.

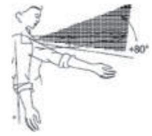
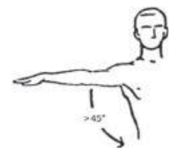
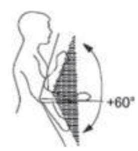
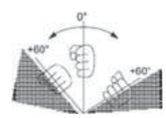
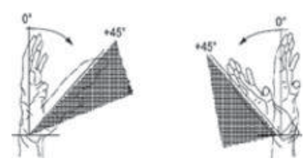
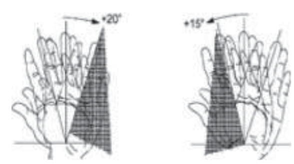
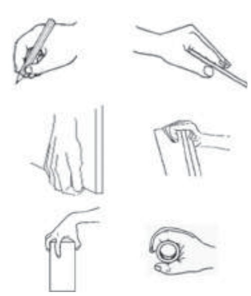
Upper limb segment	Awkward posture and movement		Risky action
[1] Shoulder	[1.1] Flexion		• Work with the arms above the head. • Need to reach something in a very high position.
	[1.2] Extension		• Need to reach something behind in a confined space.
	[1.3] Abduction		• Need to reach something behind in a confined space, or lateral from the natural position.
	[2.1] Flexion/Extension		• Need to reach a part far from the body. • Need to move or position something that need to flex the forearm.
[2] Elbow	[2.2] Pronation/Supination		• Need to rotate an object/ component. • Need to reach an object in an awkward position respect the natural one.
	[3.1] Flexion/Extension		• Need to use a tool or reposition it. • Need to insert a component in an awkward position. • Need to action a lever or make pressure
[3] Wrist	[3.2] Ulnar/radial deviation		• Need to use a tool or reposition it. • Need to insert a component in an awkward position.
	[4.1] Pinch		• Need to insert a component in an awkward position. • Handling, insertion, positioning of objects/components. • Maintain an object in position.
[4] Hand	[4.2] Grip		• Need to use a tool. • Need to maintain a component or an object in a specific position.

Table 2. Relationship between product features, assembly issues and Ergonomics aspects.

	Assemblability aspect		Ergonomics aspect	
Product feature	Handling/Insertion	Assembly issue	Body part involved	Posture #
Symmetry	Handling	To orient it in the correct position	Elbow	[2.2]
			Wrist	[3.1] – [3.2]
			Hand	[4.1]
U-shape / T-shape / etc. (open planar path and profile).	Handling	To remove tangling of components	Elbow	[2.2]
			Wrist	[3.1] – [3.2]
			Hand	[4.1]
Tapering shape (different edge loops connected)	Handling	To remove jamming and stack of components	Elbow	[2.2]
			Wrist	[3.1] – [3.2]
			Hand	[4.1]
Dimension envelope (bounding box less than 500mm^3)	Handling	To take and to keep it with one hand	Elbow	[2.2]
			Wrist	[3.1] – [3.2]
			Hand	[4.1]
Dimension envelope (bounding box more than 5dm^3 and/or weight more than 3 kg)	Handling	To take and to keep it with one hand	Elbow	[2.2]
			Wrist	[3.1] – [3.2]
			Hand	[4.1] – [4.2]
Sharping edges – thickness (distance between edges < 3 mm)	Handling	To take and to keep it	Hand	[4.1]
Flexible (splines and polylines)	Handling	To take and to keep it	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Slippery (roughness Ra < 0.4 micron)	Handling	To take and to keep it	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Symmetry	Insertion	To position correctly in the assembly	Elbow	[2.2]
			Wrist	[3.1] – [3.2]
			Hand	[4.1]
Dimension envelope (bounding box less than 500mm^3)	Insertion	To position it correctly in the assembly and to fix it.	Elbow	[2.2]
		It may require the use of special tools (tweezers, etc.)	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Dimension envelope (bounding box more than 5dm^3 and/or weight more than 3 kg)	Insertion	To position it correctly in the assembly and to fix it.	Elbow	[2.2]
			Wrist	[3.1] – [3.2]
		It may require the use of special tools (cranes, etc.)	Hand	[4.1] – [4.2]
Sharping edges – thickness (distance between edges < 3 mm)	Insertion	To hold it in right position.	Hand	[4.1]
		It may require the use of gloves.		
			Hand	[4.1]
Flexible (splines or polylines)	Insertion	To position it correctly in the assembly and to fix it.	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Insertion with interference fits (shoulder)	Insertion	To position it correctly in the assembly and to push it.	Shoulder	[1.3]
		It may require the use of tools (hammer, etc.)	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Insertion with interference fits (chamfer)	Insertion	To position it correctly in the assembly and to push it.	Shoulder	[1.3]
		It may require the use of tools (hammer, etc.)	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Screwing (threaded)	Insertion	To screw it and to clamp it.	Shoulder	[1.1] – [1.3]
		It may require the use of tools (screwdriver, etc.)	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Space limitation (O-Concentric faces)	Insertion	To position it correctly in the assembly and to fix it.	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Space limitation (S-Concentric faces with distance < 40 mm)	Insertion	To position it correctly in the assembly and to fix it.	Wrist	[3.1] – [3.2]
			Hand	[4.1]
Space limitation (Adjacent axes)	Insertion	To position it correctly in the assembly and to fix it.	Wrist	[3.1] – [3.2]
			Hand	[4.1]
...	...	...	...	...

model (i.e. native CAD file or standard exchange STEP file) is examined, by using feature recognition algorithms. The aim of this step is to obtain useful information for both assembly and ergonomics issues. The product features (symmetry, tapering, dimensions, etc.) and attributes (materials, weights, etc.) are investigated to link the assemblability aspects and ergonomics issues.

Specific rules (hints) are defined for the feature recognition process in order to extract relevant characteristics from 3D models:

- Global properties of the components: volume, bounding box sizes, weight, material;
- Global shape characteristics: axial symmetry, principal planes symmetry, stacking ratio, i.e. the ratio of the additional height due to an additional part in a stack on the height of the part;
- Specific features that are relevant to the assembly process: threaded parts, holes, pockets, etc. Diameters, lengths and other sizes are extracted for each recognized feature;
- Slenderness, i.e. the ratio between the surface and the volume of the component, which provide a measure of the flexibility of the part and its capability to be handled;
- Sharp edges, identified by the analysis of the solid angles of the concave edges or small chamfer features;
- Typical assembly patterns: pins and bolts inserted in holes or slots, etc;
- Typical arrangements of assembly patterns: flanges, linear or circular patterns of threaded connections, etc.

The retrieved features are coupled with the assembly tasks previously characterized (1st step) aiming to have all the necessary information for the successive assessments of the assemblability (e.g. B&D DfA Index) and ergonomics indices (e.g. Checklist OCRA Index).

3.3. 3rd step: definition of product features – ergonomics issues correlation

Information coming from the first and second steps is used to correlate the product features and the ergonomics aspects associated with the manual assembly tasks. The correlation law is based on the analysis of the upper limb segments, which are potentially interested by the risk of overload if awkward postures and movements are done during a manual task.

Tab. 1 illustrates the output of the analysis. A limitation of the proposed classification is that the different movements and the relative risks are considered independently. This means that the method is able to analyze only a sequential list of movements, while the effects due to complex compound lever/joint/pressure combinations are not currently considered.

After the identification of the upper limb awkward postures, it is necessary to establish how these postures are related to the product features, retrieved through the analysis of the product virtual model. In particular, the correlations between the product features, the assembly issues (retrieved from the B&D approach) and the ergonomics aspects in Tab. 1 (body parts, positions, angles, etc.) have been classified. Tab. 2 reports some representative examples of the classified correlations, while the full list has been stored in a dedicated database (Ergonomics DB in Fig. 1). It is worth to notice that in addition to the already classified correlations, the database could be customized to take into account other issues related to specific products or specific assembly tasks.

Each identified product feature affects both assemblability and ergonomics aspects, thus the optimization of the product design can certainly lead to positive impacts in terms of reduction of risks for workers, as well as minimization of the assembly time. The relationships between the product features, the manual assembly issues and the ergonomics aspects have been stored in a specific database (Ergonomics DB). The Ergonomics DB architecture and the relationships between the different items are proposed in Fig. 2.

As example of the concept underpinning this step, the following Fig. 3 illustrates the relationship among the product features, the assembly issues and ergonomics aspects in the case of a component with small dimensions. The component-bounding box, extracted from the CAD model, is used to establish if the part under analysis is too small to be manipulated by an operator in standard working conditions. Afterwards, the potential ergonomics issues are univocally identified.

3.4. 4th step: ergonomics Index evaluation

After the definition of the link between product features and ergonomics issues for each assembly task, it is possible to calculate the Ergonomics Index. The chosen metric is based on the Checklist OCRA Index [17]. This index takes into account both physical and organizational risk factors and it is calculated by using the following equation Eqn. (1):

$$\text{ErgonomicsIndex} = (F_m + Fo_m + Po_m + Ad_m) \times Rc_m \times Du_m \quad (1)$$

It is worth to notice that the Checklist OCRA Index parameters are usually retrieved by the direct observation

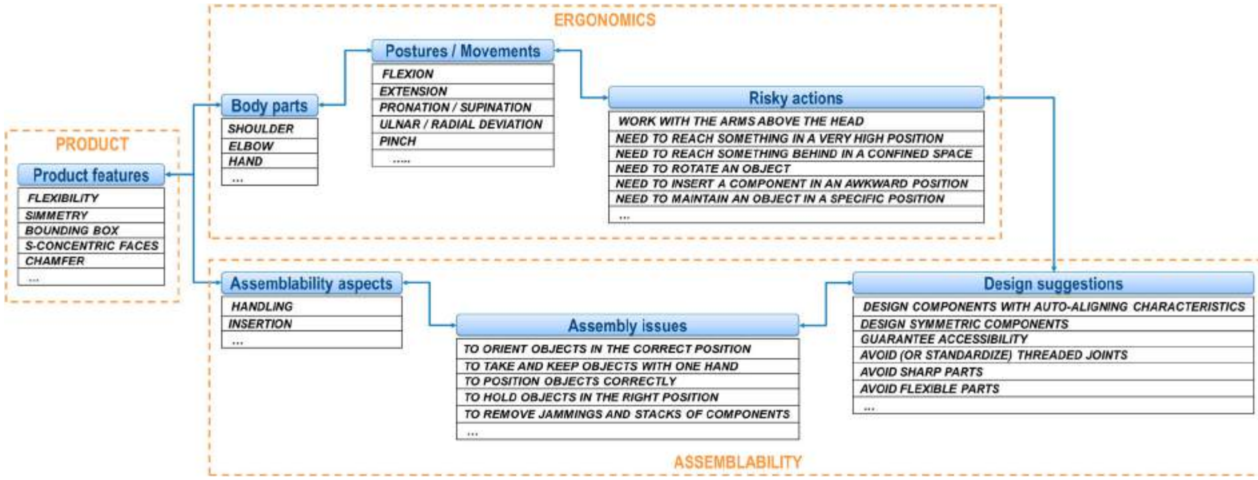


Figure 2. Simplified architecture of the Ergonomics DB.

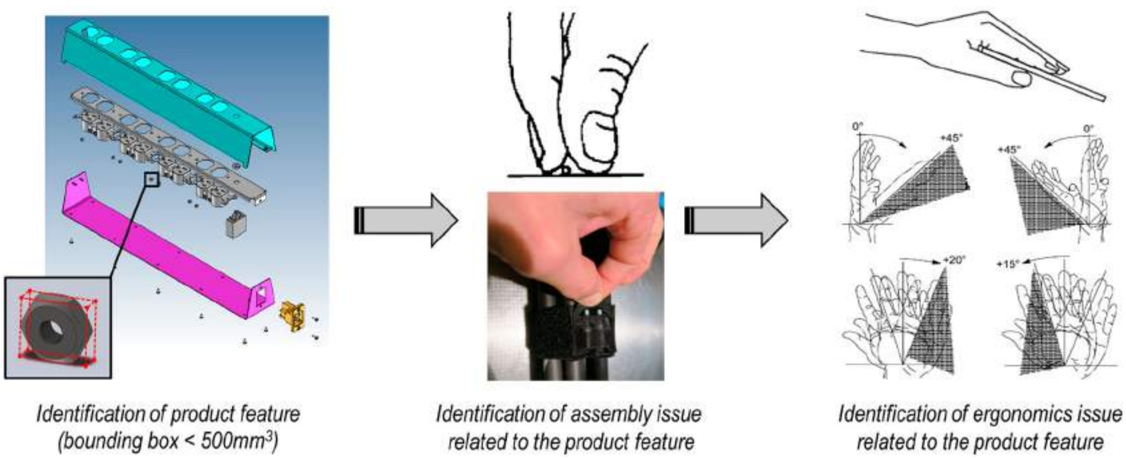


Figure 3. Example of relationship between the product features, the assembly and the ergonomics issues.

of the assembly tasks, when the assembly line/workstation is already set up. In this case, the parameters involved in the calculation of the Checklist OCRA Index cannot be retrieved by the direct observation of the assembly task, but they are estimated based on information coming from the assembly plan, the production schedule, the product virtual model and the Ergonomics DB (e.g., used assembly tools, batch size, shift duration, time cycle). Tab. 3 summarizes the parameters involved in the calculation, including the sources of information used to estimate their values.

Two items are directly correlated to product features and data stored in the Ergonomics DB:

1. *the force multiplier* (F_{Om}) value is quantified by considering the needed tools (derived from the assembly plan) and some general features (e.g. volume, weight) of the components to assemble (derived from the product virtual model);

Table 3. Details of the parameters involved in the Checklist OCRA Index.

Parameter	Definition	Source
F_m	Multiplier for the frequency of actions per minute	Production schedule Assembly plan
F_{Om}	Force multiplier	Assembly plan Product features
P_{Om}	Posture multiplier	Product features Ergonomics DB
Ad_m	Additional multiplier related to the use of tools, the exposure to vibrations or anything that could compromise the upper limbs joints and segments considered by the method	Assembly plan
Rc_m	Recovery multiplier	Production schedule
Du_m	Duration multiplier	Production schedule

2. *the posture multiplier* (P_{Om}) value is quantified by considering the product features, identified through the analysis of the product virtual model, and the relative involved body parts and postures (Tab. 1.and

Table 4. Checklist OCRA Index [17] and associated risk levels.

Checklist OCRA Index value	Risk level
0–7.5	Acceptable
7.6–11.0	Borderline
11.1–14.0	Present – low level
14.1–22.5	Present – medium level
≥ 22.6	Present – high level

Tab. 2). According to the Checklist OCRA Index, a specific value of the posture multiplier is associated to each classified posture [17].

As demonstrated by the authors who defined the Checklist OCRA Index, the value assumed by the Index is correlated with the risk for workers to develop WMSDs (Tab. 4). If a risk for workers is present, it may be mitigated modifying the product design as well as the used tools/equipment

In this step, the B&D DfA Index is assessed using the B&D software tool along with the Ergonomics Index, in order to give a complete overview of both aspects.

3.5. 5th step: product redesign

The goal of this step is to improve the product design and its assemblability, thanks to the feedbacks coming from the assessment of the Ergonomic Index, as well as the analysis of the product features. During this phase, designers are guided by rules and suggestions available in the Ergonomics DB. Tab. 5 presents some representative examples of possible design suggestions in the DB. Those suggestions seek to improve the product performances in terms of both assemblability and ergonomics.

This step can be iterated several times to modify the product features according to suggestions and checking if the ergonomics criticalities are still present. At the end, the output is the new geometry of the 3D virtual model and the new assembly plan that includes tools and equipment needed to perform the mounting tasks.

4. Case studies analysis

The proposed method has been applied on different mechatronic products (e.g., home appliances, machine tools, etc.). The following sections highlight some critical hotspots in the analysis of a wall-mounted cooker hood (Section 4.1) and a tool-holder carousel (Section 4.2). The CAD models of the analyzed products are presented in Fig. 4. These products have been chosen due to their complexity (e.g., high number of components, different types of connections, etc.) and the fact that all the components are manually assembled.

4.1. Free standing cooker hood case study

By following the general workflow of the proposed method (Fig. 1), the 1st step consists in the analysis of the manual assembly plan and the production schedule. In particular, the production rate of the current hood model is fixed to around 200 pieces per day (one shift). The assembly plan considers parallel assembly lines and specific assembly tasks are assigned to each operator. Each task has been classified, starting from the production schedule, including the items described in the method (items to assemble, liaison type, assembly time, frequency, etc.).

According to the 2nd step of the approach, the analysis of the virtual model has been performed to recognize relevant product features with the aim to identify potential ergonomics/assembly issues. In particular, here below are reported the cases of the blower system (Fig. 5) and of the electric cables (Fig. 6), in which the presence of *O-concentric faces* and of *circular section sweep on polylines* has been respectively recognized.

The first geometrical entity (i.e. *O-concentric faces*) is commonly used to provide a housing for the screws and to facilitate their insertion. The housing height is 8 mm (i.e. the circular face with bigger dimension) while the height of the screw is 6 mm (i.e. the threaded part). The screw cannot be released by assembly operators with a certain positive location. This issue potentially leads to

Table 5. Examples of design suggestions to be followed during the redesign phase.

	Benefit	
Design suggestion	Assemblability	Ergonomics
Design components with auto-aligning characteristics	To reduce the insertion time	To reduce the risk of potential problems related to wrist
Design symmetric components	To reduce the handling time	To reduce the risk of potential problems related to wrist and to pinch
Guarantee accessibility	To reduce the assembly time	To reduce the risk of posture problems for shoulder, wrist and elbow
Avoid (or at least standardize) threaded joints	To reduce the insertion time	To reduce the number of technical actions
Avoid sharp parts	To reduce the handling time	To reduce the problems for pinch
Avoid flexible parts	To reduce the handling and insertion time	To reduce the risk of potential problems related to wrist and to pinch. Reduced number of technical actions
...	...	...

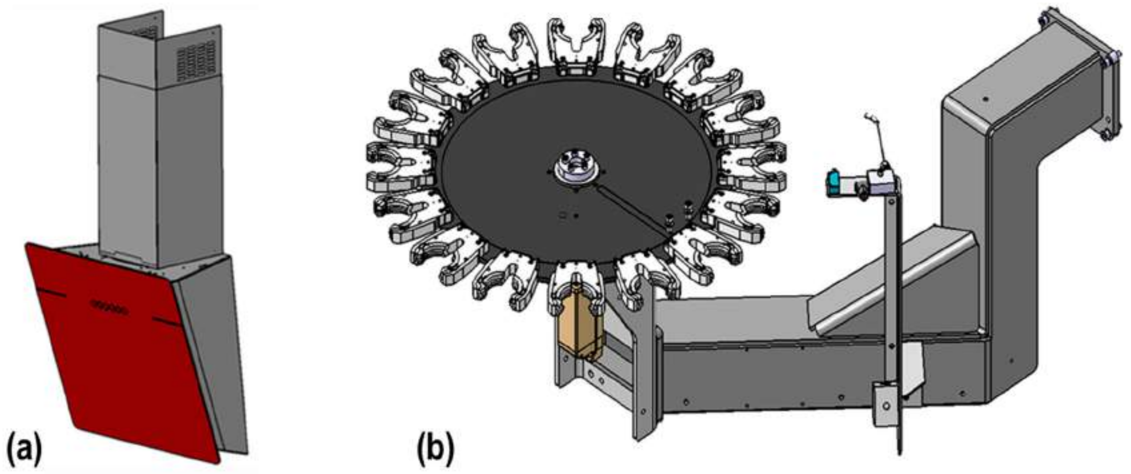


Figure 4. CAD models of the analysed products: (a) the wall-mounted cooker hood and (b) the tool-holder carousel of a CNC machine tool.

Figure 5. Identification of the critical product feature (O-Concentric faces) for the blower system.

Table 6. Ergonomics Index calculated for the blower system assembly.

	Technical actions [N°]			
Assembly tasks	DX	SX	Cycle time [s]	Ergonomics Index
Handling of screws (4 screws)	4	0	25	DX = 22.6
Positioning of screws in the housing	16	8		SX = 1.3
Insertion of screws in the housings	4	0		
Fastening of screws (with screwdriver)	9	0		

an increase in the number of technical actions during the manual assembly phase, due to the necessity for operators to continuously re-position and align the screw in the housing.

The second geometrical entity (i.e. *circular section sweep on polylines*) is a typical feature of uniform section electrical cables, which are flexible (especially for small dimensions). This characteristic entails an issue in the placement of the cable in its routing and fixing. This issue is a source of physical effort (depending on the number of cables and their size) and generally requires a high number of technical actions.

Based on the relationships classified in the Ergonomics DB (3rd step), *O-Concentric faces* feature is correlated to a limited space for operators during the assembly task "Insert M4 × 6 screws into the blower screw housing" (Tab. 6). Such issue potentially leads to awkward postures of the wrist and hand due to screw handling and positioning operations. According to Tab. 2, flexion / extension of

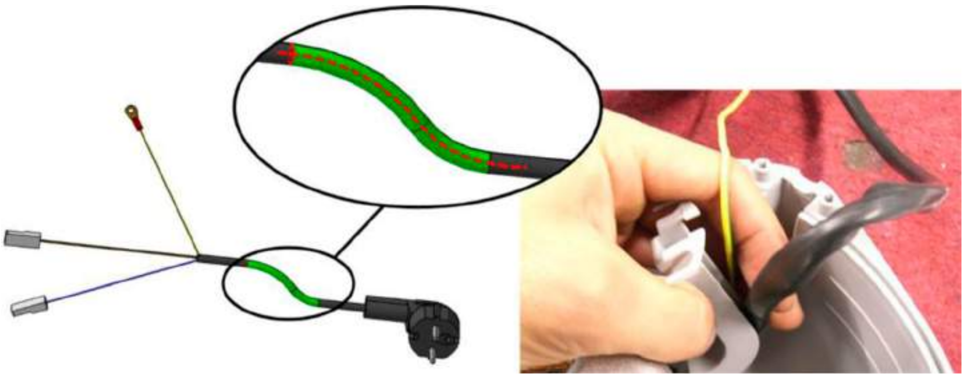


Figure 6. Identification of the critical product feature (*circular section sweep on polylines*) for the cable.

Table 7. Ergonomics Index calculated for the cable assembly.

Assembly tasks	Technical actions [N°] DX	SX	Cycle time [s]	Ergonomics Index
Handling of cable	1		22	DX = 11.3
Handling of plastic cover		1		SX = 0.6
Positioning of cable into plastic cover	5			
Placing of plastic cover and cable in the support	2			
Fastening of plastic cover and cable in the support (2 screws)	6	4		

the wrist, ulnar / radial deviation of the wrist and pinch difficulties for the hand criticalities can emerge.

On the other hand, considering the *circular section sweep on polylines* feature, a high number of technical actions is required during the manual assembly task "Positioning of cable into plastic cover" (Tab. 7), due to a set of subsequent tasks to adapt the shape of the cable to the shape of the plastic cover. Again, this issue potentially leads to an awkward posture of wrist and hand.

The assessment of the Checklist OCRA Index has been carried out (4th step) to confirm the potential issues preventively identified with the feature analysis. Results of the Ergonomics Index assessment for the blower and for the cable are respectively reported in Tab. 6 and Tab. 7. In the case of the blower, the assessment highlights a possible serious risk for the right upper limb (high level): 33 technical actions per 25 s. The left upper limb, on the contrary, does not present a potential risk. Similarly, in the case of the cable, the Ergonomics Index calculated for the right side highlights a possible risk for workers (present - low level) due to the awkward posture of the hand. The left side does not present a potential risk.

Possible redesign actions (5th step) can be implemented to solve or to mitigate the identified issues, such as the blower housing height reduction (e.g. max 5 mm). By implementing this simple design suggestion, the Ergonomics Index value would decrease from 22.6 to 17.3 for the right side, reducing the ergonomics risk from high level to medium level. It is worth to notice that also the cycle time will decrease from 25 s. to 16 s, with a clear advantage in terms of assembly time and thus production cost.

4.2. Tool-holder carousel of CNC machine tool

In this second example, the production rate is much lower than the hood (10 vs. 200 pieces per day) and the assembly tasks are performed in different assembly workplaces (islands), considering the Lean Six Sigma philosophy adopted by the company and reflected in the assembly plan. By using the production schedule document, each task has been classified according to the 1st step of the methodology (items to assemble, liaison type, assembly time, frequency, etc.).

The analysis of the virtual model (2nd step) allows the identification of several features related to the assembly and ergonomics issues previously described. Two examples are here reported: the carousel head and the bracket support, in which the presence of *bounding box* $< 500mm^3$ (Fig. 7) and of *S-Adjacent faces D* < 40 *mm* (Fig. 8) has been respectively recognized.

The first geometrical entity (i.e. *bounding box* $< 500mm^3$) is a typical aspect of small items such as screws, grubs, washers, etc. This feature entails an issue in the component picking, handling and insertions. This issue

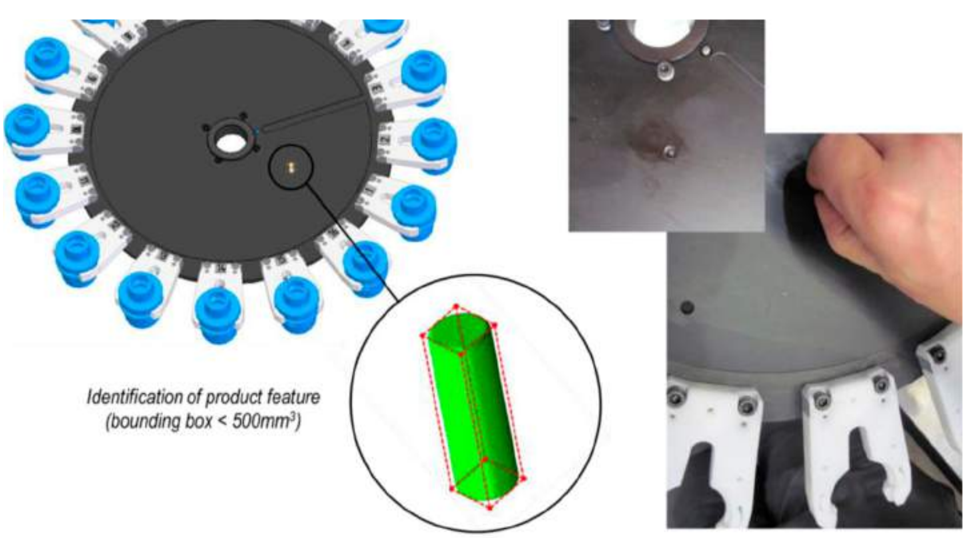


Figure 7. Identification of the critical product feature (*bounding box* $< 500mm^3$) for the grub screw of the carousel head.

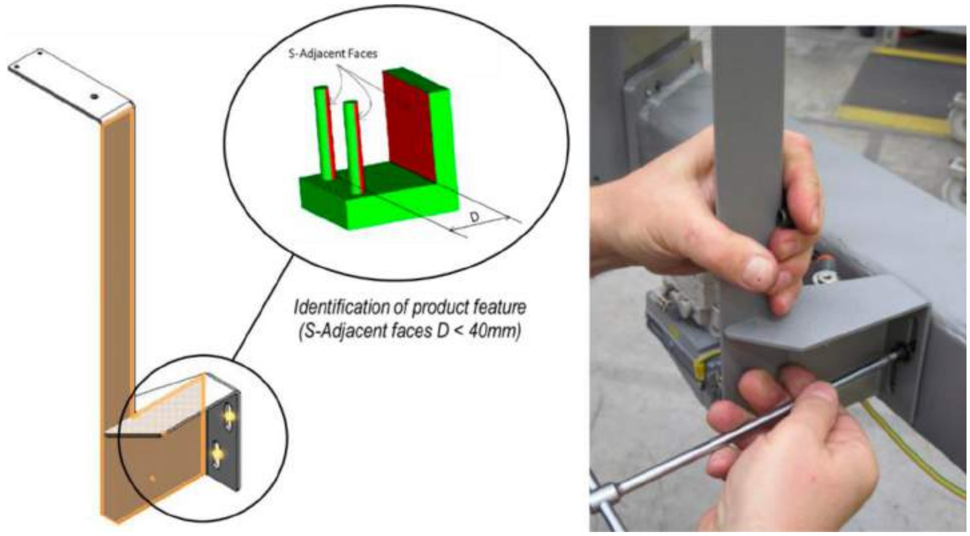


Figure 8. Identification of the critical product feature (*S-Adjacent faces* $D < 40\,mm$) screws for the bracket support.

Table 8. Ergonomics Index calculated for the grub assembly.

	Technical actions [N°]			
Assembly tasks	DX	SX	Cycle time [s]	Ergonomics Index
Picking of grub from the box	2		36	DX = 7.9 SX = Not active
Positioning of grub in carousel head	3			
Inserting of grub in carousel head	3			
Fastening of grub (first with hands and then with the screwing tool)	12			

Table 9. Ergonomics Index calculated for the bracket assembly.

	Technical actions [N°]			
Assembly tasks	DX	SX	Cycle time [s]	Ergonomics Index
Handling of bracket	1		64	DX = 12.0 SX = 4.5
Positioning of bracket into support	3			
Keeping of bracket into position	1			
Handling of 1st bolt		1		
Positioning of 1st bolt		1		
Fastening of 1st bolt into bracket and support (with screwing tool)		11		
Handling of 2nd bolt		1		
Positioning of 2nd bolt		1		
Fastening of 2nd bolt into bracket and support (with screwing tool)		11		

potentially leads to an increase in the number of technical actions during the manual assembly phase.

The second geometrical entity (i.e. *S-Adjacent faces* $D < 40\,mm$) refers to components which have been wrongly designed, without considering the needed space for hands and tools. This characteristic entails an issue in the component placement and positioning, as well as in the time required for the component fixing. This issue is a source of physical effort due to the long time required to grasp the component during the bolts screwing.

According to the relationships classified in the Ergonomics DB (3rd step), *bounding box* $< 500mm^3$ feature is correlated to a potential ergonomics issue of elbow, wrist and hand during the assembly task "Pick, place and screw the M4 × 12 grub into the carousel head" (Tab. 8). *S-Adjacent face* $D < 40\,mm$ feature is correlated to a potential ergonomics issue of wrist and hand during the assembly task "Fix the bracket to the support using 2 bolts M8 × 10" (Tab. 9).

The assessment of the Checklist OCRA Index has been carried out (4th step) to confirm the potential issues preventively identified with the feature analysis. Results of the Ergonomics Index assessment for the grub and for the bracket are respectively reported in Tab. 8 and Tab. 9. In the case of the grub, the assessment highlights a low risk for the right upper limb (borderline): 20 technical actions per 36 s. The left upper limb, on the contrary, is not active in this task. In the case of the bracket, the assessment of Ergonomics Index for the right side highlights a possible risk for workers (present - low level) due to the grasping effort of the hand. The left side does not present a potential risk.

Possible redesign actions (5th step) can be implemented to solve or to mitigate the identified issues. For example, in the case of the bracket the general suggestion is to increase the distance D between the axis and the part face. From this suggestion, different redesign actions can be implemented based on designer skills, such as:

- Enlarge the bracket part where the screws are fixed. This solution increases the accessibility during the screwing operations;
- Reposition the bracket part where the screws are fixed in the upper part of the tool-holder support and not on the side.

Both the proposed design alternatives aim to increase the product assemblability and to reduce the value of the Ergonomics Index (Acceptable Risk level).

5. Conclusions and future research

This paper presents a novel approach to product redesign, as it considers manual assembly tasks from an ergonomics perspective. Ergonomics issues are highlighted during the product development phase by the recognition of possible critical features in the 3D model of a product.

The main step beyond the state of the art is the correlation between product features, retrieved from the product virtual representations, and ergonomics issues related to the assembly tasks. Through the proposed method, ergonomics issues can be faced during the design phase, when there is the necessary degree of freedom to modify the product and its assembly plan. This study is grounded on the concept that it is better to prevent potential issues of the assembly phase, by improving relevant product features, rather than studying and implementing remedial actions at the assembly site and/or workstation. The proposed case studies confirm the possibility to identify ergonomic criticalities through the analysis of the product features and attributes retrieved from the 3D CAD model, demonstrating with analytic measures the effectiveness of the approach in real production/assembly contexts.

The approach presents few limitations. Firstly, it is not able to consider complex compound lever/joint/pressure combinations, but only subsequent and independent actions of the upper limbs. Secondly, the nature of the Ergonomics DB is general and open to host new patterns and features, but it is incomplete and needs to be filled with other items. This aspect is part of the next research work.

Future research will be focused on implementing the proposed approach in a software tool which is able to automatically recognize geometrical features from 3D CAD model. This is certainly an essential improvement to guarantee the applicability of the approach in real industrial contexts, where time and resources (both human and economic) are always limited. Another interesting aspect will be the integration of the proposed approach with AR/VR tools supported by Microsoft Kinect application, which is able to learn the upper limbs movements for a more realistic analysis and a fast calculation of both assembly and ergonomics indices.

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References

[1] Babic, B.; Nesic, N.; Miljkovic, Z.: A review of automated feature recognition with rule-based pattern recognition, Computers in Industry, 59(4), 2008, 321–337. http://doi.org/10.1016/j.compind.2007.09.001

[2] Battini, D.; Faccio, M.; Persona, A.; Sgarbossa, F.: New methodological framework to improve productivity and ergonomics in assembly system design, International Journal of Industrial Ergonomics, 41(1), 2011, 30–42. http://doi.org/10.1016/j.ergon.2010.12.001

[3] Boothroyd, G.; Dewhurst, P.; Knight, W. A.: Product Design for Manufacture and Assembly – Third Edition, CRC Press, Boca Raton, FL, 2010.

[4] Chryssolouris, G.; Mvrikios, D.; Fragos, D.; Karabatsou, V.: A virtual reality-based experimentation environment for the verification of human-related factors in assembly processes, Robotics and Computer-Integrated Manufacturing, 16(4), 2000, 267–276. http://doi.org/10.1016/S0736-5845(00)00013-2

[5] Cimino, A.; Mirabelli, G.: Modeling, simulation and ergonomic standards as support tools for a workstation design in manufacturing system, International Journal of Simulation and Process Modeling, 5(2), 2009, 138–148. http://doi.org/10.1504/IJSPM.2010.03266

[6] Do Amaral, A.; Menegon, N. L.: The use of design for assembly (DFA) method for ergonomics improvement of a design, Product Management & Development, 5(1), 2007, 33–40.

[7] Gao, J.; Zheng, D.; Gindy, N.: Mathematical representation of feature conversion for CAD/CAM system integration, Robotics and Computer-Integrated Manufacturing, 20(5), 2004, 457–467. http://doi.org/10.1016/j.rcim.2004.05.001

[8] Garg, A.; Moore, J. S.; Kapellusch, J. M.: The Revised Strain Index: an improved upper extremity exposure assessment model, Ergonomics, 2016. http://doi.org/10.1080/00140139.2016.1237678

[9] Hoque, A. S. M.; Halder, P. K.; Parvez, M. S.; Szecsi, T.: Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost under CAD/CAM environment, Computers & Industrial Engineering, 66(4), 2013, 988–1003. http://doi.org/10.1016/j.cie.2013.08.016

[10] Hoyos-Ruiz, J.; Martínez-Cadavid, J. F.; Osorio-Gómez, G.; Mejía-Gutiérrez, R.: Implementation of ergonomic aspects throughout the engineering design process: Human-Artefact-Context analysis. International Journal on Interactive Design and Manufacturing (IJIDeM), 2015, 1-15. http://doi.org/10.1007/s12008-015-0282-3

[11] Jong, W.R., Lai, P.J., Chen, Y.W., Ting, Y.H.: Automatic process planning of mold components with integration of feature recognition and group technology, International Journal of Advanced Manufacturing Technology, 78(5), 2015, 807–824. http://doi.org/10.1007/s00170-014-6627-4
[12] Lai, J.-Y.; Wang, M.-H.; Chiu, Y.-K.; Hsu, C.-H.; Tsai, Y.-C.; Huang, C.-Y.: Recognition of depression and protrusion features on B-rep models based on virtual loops, Computer Aided Design and Applications, 13(1), 2016, 95–107. http://doi.org/10.1080/16864360.2015.1059200
[13] Lupinetti, K.; Chiang, L.; Giannini, F.; Monti, M.; Pernot, J.-P.: Regular patterns of repeated elements in CAD assembly model retrieval, Computer Aided Design and Applications, 14(4), 2017, 516–525. http://doi.org/10.1080/16864360.2016.1257193
[14] Mali, S. C.; Vyavahare, R. T.: An Ergonomic Evaluation of an Industrial Workstation: A Review, International Journal of Current Engineering and Technology, 5(3), 2015, 1820–1826.
[15] Mandorli, F.; Otto, H. E.; Kimura, F.: A Reference Kernel Model for Feature-Based Cad Systems Supported by Conditional Attributed Rewrite Systems, Proceedings of ACM/IEEE Symposium on Solid Modeling and Applications ‘93, 1993, 343–354.
[16] Niu, Z.; Martin, R. R.; Langbein, F. C.; Sabin, M. A.: Rapidly finding CAD features using database optimization, Computer-Aided Design, 69, 2015, 35–50. http://doi.org/10.1016/j.cad.2015.08.001
[17] Occhipinti, E.; Colombini, D.: The occupational repetitive action (OCRA) methods: OCRA index and OCRA checklist, In Eds. Stanton N.Et al., Handbook of human Factors and ergonomics methods, CRC Press, Boca Raton, FL, 2004.
[18] Oussama, J., Abdelilah, E., Ahmed, R.: Manufacturing Computer Aided Process Planning For Rotational Parts. Part 1: Automatic Feature Recognition from STEP AP203 Ed2, International Journal of Engineering Research and Application, 4(5), 2014, 14–25.
[19] Rahmani, K.; Arezoo, B.: Boundary analysis and geometric completion for recognition of interacting machining features, Computer Aided Design, 38(8), 2006, 845–856. http://doi.org/10.1016/j.cad.2006.04.015
[20] Shinde, G. V.; Jadhav, V. S.: Ergonomic analysis of an assembly workstation to identify time consuming and fatigue causing factors using application of motion study, International Journal of Engineering and Technology, 4(4), 2012, 220–227.
[21] Tan, C. F.; Kher, V. K.; Ismail, N.: Design of a Feature Recognition System for CAD/CAM Integration, World Applied Sciences Journal, 21(8), 2013, 1162–1166. http://doi.org/10.5829/idosi.wasj.2013.21.8.2126
[22] Zheltoukhova, K.: Musculoskeletal Disorders and Work – Results of a survey of individuals living with Musculoskeletal Disorders in six European countries, The Work Foundation (Lancaster University), Great Britain, 2013.
[23] Zhu, H.; Menq, C. H.: B-Rep model simplification by automatic fillet/round suppressing for efficient automatic feature recognition, Computer Aided Design, 34(2), 2002, 109–123. http://doi.org/10.1016/S0010-4485(01)00056-2