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A model for complexity assessment in manual assembly operations through predetermined motion time systems

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Abstract

Manual assembly processes are favoured for supporting low volume production systems, high product variety, assembly operations that are difficult to automate and manufacturing in low-wage countries. However, manual operations can dramatically impact assembly cycle times, quality and cost when the complexity of the manual operation increases. This paper proposes a method for assessing the process complexity of manual assembly operations, using a representation of manual operations based on predetermined motion time systems. The purpose of this framework is to provide a tool that can be used practically to assess, and therefore control, the complexity of manual operations during their design.

Keywords: Manual assembly; Task complexity; Complexity management; MODAPTS.

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1. Introduction

A flexible assembly line requiring high precision typically favours manually assembly accomplished by skilled and experienced human operators [1]. During manual assembly operations, workers are confronted with multiple sources of information and need to make decisions concerning a process under a strict time pressure. However, the intrinsic mental and physical abilities or limitations of human worker have to be taken into account when designing work processes in order to achieve requirements in terms of process quality and cycle time. This can be achieved through analysing and controlling complexity of the process with appropriate information and rigorous work sequence planning [2].

In related literature, complexity of assembly tasks is largely examined by focusing only on physical characteristics of the parts/products to be assembled. Boothroyd et al. developed Design for Assembly (DFA) method based on a large number of empirical investigations to evaluate the difficulty of assembly tasks and to roughly estimate the assembly times [3]. Hinckley proposed an assembly complexity factor that associated the number of assembly operations and time to assembly related failures [4]. Shibata et al. extended Hinckley's methodology to predict the degree of assembly faults based on the complexity level of individual assembly steps [5]. Kim proposed a metric that measures the process complexity based on a combination of system elements [6]. ElMaraghy and Urbanic designed a complexity measure for manual manufacturing operations which takes some facets of cognitive factors [7]. Zaeh et al. proposed a multi-dimensional complexity model for manual assembly operations which extended the concept of systems of predetermined times by including actual human performance, attention allocation and learning effects [2]. Furthermore, Samy and ElMaraghy presented a product assembly complexity model that can be used as a decision support tool for designers to reduce potential assembly complexity and associated costs [8].

Complexity of assembly operations can be practically predicted through the physical features of objects that affect the difficulty of its assembly. However, such approaches address only isolated and individual assembly processes without directly accounting the interactions between cognitive processes, attention allocation, and workspace and design limitations. This article presents a complexity modelling approach based on Predetermined Motion Time Systems (PMTS) which is facilitated by virtual manufacturing (VM).

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The proposed model extends PMTS by including dimensions of physical and cognitive task performance and is implemented as a module within the vueOne virtual manufacturing tool developed by the Automation Systems Group (ASG) at the University of Warwick. This research contributes to the body of knowledge and supports industry in three main ways. Firstly, the proposed model can support in identifying and comparing manual assembly process complexity to determine an optimal approach using an objective, quantitative method. Secondly, the model allows the designer to identify the complexity sources so that process design changes to search for an optimal are better informed. Finally, this approach supports concurrency between product design and manufacturing system design, highlighting potential problem areas prior to commissioning, reducing costs, product realisation time and increase the efficiency of the organisation. PMTS are commonly used to describe assembly sequences in labour oriented industries, thus the proposed method is a practical and economical way to assess task complexity in manual assembly stations. Furthermore, it can support process designers to select optimum task sequences which offer ease of operation and reduced physical and cognitive workload on workers. The nomenclature used in the paper is presented in Table 1.

Table 1. Nomenclature

$C_{op,i}$	Overall operation complexity of i^{th} operation
$C^{*}_{op,i}$	$C_{op,i}$ with variation factor
$C^{k}_{op,i}$	Overall operation complexity of k^{th} variation of i^{th} operation
OCI_i	Operational complexity index of i^{th} operation
v_i	Product variation factor of i^{th} operation
$P_{k,i}$	Product mix ratio of k^{th} variant in i^{th} operation
$N_{k,i}$	Number of product variants entered to i^{th} operation
S_i	Size factor of i^{th} operation
N_i	Total number of tasks in i^{th} operation
$n_{m,j,i}$	Total number of movement activity in j^{th} task of i^{th} operation
$n_{t,j,i}$	Total number of terminal activity in j^{th} task of i^{th} operation
$n_{a,j,i}$	Total number of auxiliary activity in j^{th} task of i^{th} operation
D_i	Diversity factor of i^{th} operation
$d_{act,i}$	Diversity ratio of activities in i^{th} operation
$d_{task,i}$	Diversity ratio of task in i^{th} operation
$N_{dm,i}$	Number of distinct task with at least one movement activity
$N_{m,i}$	Number of task with at least one movement activity
$N_{dt,i}$	Number of distinct task with at least one terminal activity
$N_{t,i}$	Number of task with at least one terminal activity
$N_{da,i}$	Number of distinct task with at least one auxiliary activity
$N_{a,i}$	Number of task with at least one auxiliary activity
$n_{dm,j,i}$	Number of distinct movement activity in j^{th} task of i^{th} operation
$n_{dt,j,i}$	Number of distinct terminal activity in j^{th} task of i^{th} operation
$n_{da,j,i}$	Number of distinct auxiliary activity in j^{th} task of i^{th} operation
E_i	Effort penalty factor of i^{th} operation
$e_{m,z,j,i}$	Effort penalty of z^{th} movement activity in j^{th} task of i^{th} operation
$e_{t,z,j,i}$	Effort penalty of z^{th} terminal activity in j^{th} task of i^{th} operation
$e_{a,z,j,i}$	Effort penalty of z^{th} auxiliary activity in j^{th} task of i^{th} operation

2. Predetermined motion time systems

PMTS are work measurement systems which are used to calculate basic labour rates for an assembly line [9]. Typically, PMTS breaks down the entire operation to basic human movements and classifies each of them based on the nature of the movement (i.e. motional elements such as grasp, put and reach, and mental functions such as identify, locate and decide) and the condition in which the movement is being performed. Most common PMTS methods include; Modular Arrangements of Predetermined Time Standards (MODAPTS) [10], the methods time measurement [11] the Maynard Operation Sequence Technique (MOST) [12] and Master standard data [13]. In this research, MODAPTS was selected because it is used by the research project partners i.e. Ford Motor Company and Jaguar Land Rover. In MODAPTS, elements and functions are coded alpha-numerically, the letter describes the activity and the associated number is the completion time for the corresponding activity, expressed using MODs as a unit of time (one MOD equals to 0.129 seconds). MODAPTS classifies basic operator activities into three classes: movement, terminal and auxiliary. Movement class elements refer to movements through space with a finger-hand-arm-shoulder-trunk system. Terminal class activities are carried out at the end of a movement and in close proximity to the things being worked on. Auxiliary class refers to activities that do not include movement class, such as: juggling, deciding and reading. A work element can be formed using MODAPTS through combining activities being performed and identifying the corresponding MODS that indicates the time values required to complete the work element. For example, a work element can be coded as “M2G1”, with “M2” meaning moving the arm with two mods and “G1” means getting a workpiece with one MOD. The estimated time for this work element is therefore, 0.387 s (3×0.129 s). The MOD time increment value reflects the average abilities of a work force (i.e. age, gender, skills) in achieving a given activity.

3. Modelling of operational complexity

Human operators are subjected to various tasks of different complexities, ranging from simple pick and place operations to complex multi-dimensional joining operations. According to Falck et al. [14], assembly complexity, assembly time and action cost are strongly related. Thus, in order to increase the efficiency of an assembly operation, complex assembly solutions should be avoided. Based on the review of the related literature, sources of complexity in manual assembly operations are categorized into four groups: (*i*) product related factors which are composed of material, design and special specifications for each part or subassembly within the product [8,14], (*ii*) process related factors include effects induced by selected assembly methodology, sequences and volume requirements as well as the effects of product variation, operational uncertainties, process dependencies, insufficient work instructions [2,8,14–16], (*iii*) personal factors consist of several elements which affect the perceived complexity by the operator such as: mental and physical capacity of the operator, his/her training level, corresponding manufacturing knowledge, personality, culture and motivation to work [2,14,17,18] and (*iv*) environmental factors that affect the performance of the human operator and comfort of the assembly task e.g. workspace ergonomics, heat stress, confined space [14]. In the initial design stages of manual assembly operations much of this information is either unavailable of difficult to obtain requiring a time consuming and costly investigation phase To solve this problem this research presents a model to practically assess complexity that aggregates data available at the early design phase (number and variety of process elements and the required cognitive/physical effort to complete the operation) from existing engineering design tools to objectively evaluate and compare design alternatives. This is achieved through a reductionism approach based on PMTS descriptions and the complexity model introduced by ElMaraghy and Urbanic [7]. This model consists of three factors: the absolute quantity of information, the diversity of information and the information content. In the current work, an assembly operation is considered as a hierarchical structure consists of a series of tasks that are themselves composed of a series of basic operator activities. The operational complexity index OCI_i is a function of the total number and diversity of tasks and movements, terminal and auxiliary activities as well as the effort required to complete these activities. The process for determining OCI_i is as follows:

a) ***Operation decomposition*** commences by stating the overall goal that the operator has to achieve. This is then re-described in a series of tasks (e.g. picking, placing, fitting etc.) which are composed of basic operator activities.

b) ***Conducting MODAPTS analysis*** to translate operator activities into element classes (codes and time values). An increase in the detail of PMTS coding results in a higher accuracy complexity assessment therefore every operator activity should be coded appropriately by including design factors, environmental limitations and operational decisions.

c) ***Analysis of activity effort*** to detect and evaluate activities that affect operator performance and work comfort in an assembly task. Operations that require higher physical and cognitive effort are more difficult for operators to gain proficiency in [7]. In this research, a task effort penalty is assigned to simulate this effect. The assigned penalty factor represents the degree of effort required to complete the activity by a qualified, thoroughly experienced person. A subjective classification which is similar to Quality Function Deployment (QFD) is used to characterize basic operator activities described in the MODAPTS based on their influence on the work performance i.e. natural body activities (0), activities that require some effort (.5) and activities that impede the overall work performance (1). The assigned effort penalties for movement (e_m), terminal (e_t) and auxiliary (e_a) activities are defined in Table 2. Activity effort is analysed through calculating an effort penalty matrix. Columns of the proposed matrix represents the average degree of effort required to complete each movement, terminal and auxiliary activity in a given assembly operation, respectively. The effort penalty factor of i^{th} operation, E_i, is calculated as follows;

$$E_i = [\frac{\sum_1^{N_i}\sum_1^{n_{m,j,i}} e_{m,z,j,i}}{\sum_1^{N_i} n_{m,j,i}} \; \frac{\sum_1^{N_i}\sum_1^{n_{t,j,i}} e_{t,z,j,i}}{\sum_1^{N_i} n_{t,j,i}} \; \frac{\sum_1^{N_i}\sum_1^{n_{a,j,i}} e_{a,z,j,i}}{\sum_1^{N_i} n_{a,j,i}}] \tag{1}$$

d) ***Analysis of diversity***: Identical, repetitive activities have a reduced impact on complexity [7]. To model the reduction in complexity as activities and tasks are repeated, a generic diversity factor is proposed. In this paper, the diversity of an operation is captured within two distinct levels, i.e. activity and task. In the activity level, a diversity ratio matrix, $d_{act,i}$, between the total and distinct number of activities of different classes is represented by Eq. 2.

$$d_{act_i} = [\frac{\sum_1^{N_i} n_{dm,j,i}}{\sum_1^{N_i} n_{m,j,i}} \; \frac{\sum_1^{N_i} n_{dt,j,i}}{\sum_1^{N_{i,k}} n_{t,j,i}} \; \frac{\sum_1^{N_i} n_{da,j,i}}{\sum_1^{N_{i,k}} n_{a,j,i}}] \tag{2}$$

Similar to analysis of repeated activities, another diversity ratio matrix at task level is introduced to reflect the effects of repeated tasks (Eq. 3):

$$d_{task_i} = \begin{bmatrix} \frac{N_{dm,i}}{N_{m,i}} & 0 & 0 \\ 0 & \frac{N_{dt,i}}{N_{t,i}} & 0 \\ 0 & 0 & \frac{N_{da,i}}{N_{a,i}} \end{bmatrix} \tag{3}$$

The diversity factor of an operation is calculated in Eq. 4:

$$D_i = d_{act_i} d_{task_i} \tag{4}$$

e) ***Analysis of operation size:*** A complex task may be divided into several effortless simple steps [7]. Therefore, along with the factors of effort and diversity, activity size is also assessed in the proposed approach by introducing a size factor. The proposed size factor for operation i (S_i) is calculated as follows;

$$S_i = \begin{bmatrix} log_2(\sum_1^{N_i} n_{m,j,i} + 1) & 0 & 0 \\ 0 & log_2(\sum_1^{N_i} n_{t,j,i} + 1) & 0 \\ 0 & 0 & log_2(\sum_1^{N_i} n_{a,j,i} + 1) \end{bmatrix} \tag{5}$$

f) ***Analysis of operation complexity index* (*OCI*$_i$)*:*** represents the complexity arising in a single product assembly operation due to factors such as: assembly difficulty, workplace restrictions (e.g. reachability, visibility issues etc.) and product limitations (e.g. handling difficulty etc.). The *OCI* score of operation *i* is calculated as follows;

$$OCI_i = [(E_i + D_i)S_i] \tag{6}$$

Increased operational complexity is thus captured with a higher *OCI* score from which the inference is drawn for increased operation susceptibility to human error. The summation of all elements within the OCI_i matrix gives the overall operation complexity ($C_{op,i}$) of an assembly operation for a given product.

$$C_{op,i} = OCI_{i(1,1)} + OCI_{i(1,2)} + OCI_{i(1,3)} \tag{7}$$

While $C_{op,i}$ gives an indication of total complexity of an operation, it does not capture the complexity of product variants. There is an additional layer of complexity associated with the introduction of variants which is perceived by the operator in a real-world setting, but cannot be captured by MODAPTS alone. Although beyond the core scope of this research, the authors propose a variation factor, v_i (Eq. 8), for assessing the impact of product variants which will be tested and validated in future work. The variation factor is based on information entropy developed by [19]. A weighted average complexity score $C^*_{op,i}$ of a manual assembly operation that accommodates multiple product variants is given by Eq. 9

$$(v_i = 1 - (\sum_1^{N_{k,i}} P_k \, log_2 P_k)) \tag{8}$$

$$C^*_{op,i} = v_i(\sum_1^{N_{k,i}} P_k C_{op,i}^{N_{k,i}}) \tag{9}$$

Table 2. Calculation of qualitative normalized activity effort penalties (This table is produced by modifying approach in [10] with suggestions from [9])

Class	Type	Description				Denotation	MODs	Natural activities requiring little effort	Activities requiring some effort	Activities that impede work performance	Effort penalty e_m, e_t and e_a
Movement	Finger	Finger moves (2.5 cm)				M1	1	■			0.00
	Hand	Hand moves (5 cm)				M2	2	■			0.00
	Forearm	Forearm moves (15 cm)				M3	3	■			0.00
	Full arm forward	Full arm forward moves (30 cm)				M4	4			■	1.00
	Full arm outward	Full arm outward moves (45 cm)				M5	5			■	1.00
	Trunk	Trunk moves (75 cm)				M7	7			■	1.00
	Walk	Walk or turn per pace (50 cm)				W5	5		■		0.50
	Bending	Bending and straightening up				B17	17			■	1.00
Terminal	Get	Touching with the tips of the fingers				G0	0	■			0.00
		Grasping object [9]	α+β≤360	Size ≥ 15 mm	Non-tangling	G1	1	■			0.00
			α+β≤360	Size ≥ 15 mm	Tangling	G3	3			■	1.00
			α+β≤360	Size < 15 mm	Non-tangling	G1	1	■			0.00
			α+β≤360	Size < 15 mm	Tangling	G3	3			■	1.00
			360<α+β≤540	Size ≥ 15 mm	Non-tangling	G1	1	■			0.00
			360<α+β≤540	Size ≥ 15 mm	Tangling	G3	3			■	1.00
			360<α+β≤540	Size < 15 mm	Non-tangling	G3	3			■	1.00
			360<α+β≤540	Size < 15 mm	Tangling	G3	3			■	1.00
			540<α+β≤720	Size ≥ 15 mm	Non-tangling	G3	3			■	1.00
			540<α+β≤720	Size ≥ 15 mm	Tangling	G3	3			■	1.00
	Put	Placing an object to a general location				P0	0	■			0.00
		Placing object [9]	Visible	Holding down not required		P1	1	■			0.00
			Visible	Holding down required		P2	2		■		0.50
			Invisible	Holding down not required		P5	5			■	1.00
			Invisible	Holding down required		P5	5			■	1.00
Auxiliary	Read	Read one word in a group of words				R2	2		■		0.50
		Read one word (proof reading or verifying)				R3	3		■		0.50
	Juggle	Change in the position of a grasp				J2	2		■		0.50
	Foot	One direction foot movement				F3	3	■			0.00
	Crank	One revolution performed with the forearm				C4	4	■			0.00
		One revolution performed with the wrist				C3	3	■			0.00
	Vocalize	Each word spoken				V3	3		■		0.50
	Eye	Mental recognition				E2	2		■		0.50
		Movement of the eye; up, down, left and right				E2	2		■		0.50
		Changing shape of the lens				E4	4		■		0.50
	Decision	Binary decisions				D	3			■	1.00
	Load & Extra force	Applied force, part lifting				L, X	-		■		0.50
	Count	Per items when the items are arranged				N3	3		■		0.50
		Per items when the items are disarranged				N6	6		■		0.50

4. Case study

The proposed assessment model is tested in the vueOne VM tool. This tool utilizes a 3D environment in which automated, semi-automated and manual operations can be modelled, simulated and validated in a virtual environment. Manual operations are modelled in the vueOne tool using the *V-Man* (Virtual Manikin) module which simulates interactions (i.e. process interlock) between the operator and the manufacturing environment i.e. tools and equipment. In vueOne, the time taken to complete an action of digital human model is characterised by MODAPTS, thus all movements recorded in the simulation can be exported in the MODAPTS format. This data is fed directly into the complexity model presented in this paper. Fig. 1 represents the interaction between the virtual process planning tool and the proposed complexity assessment method.

The proposed assessment model evaluates two process designs of an automotive engine bearing liner assembly operation designed in the vueOne VM for a single product. The operation consists of picking and fitting three different bearing liners with a quality check on the final assembly. Processes include 27 tasks for both designs and the cycle times to complete operations are recorded as 33.969 and 24.167 secs for Design A and Design B, respectively.

The process work sequence plan of Design A is given in Table 3 and the corresponding assembly workstation is

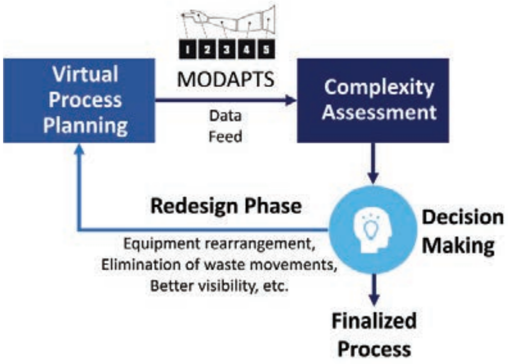

Fig. 1. The integration of the proposed methodology with the virtual process planning tool to realize decision-making mechanism in the design evaluation

Table 3. Process work sequence of Design A
(Size<15mm, α+β≤360, Non-tangling, Invisible, Holding down required)

	Task	Code	MODs
1 (A)	Move to rack	W5*2	10
2 (B)	Search for orange bearing type	E2E2	4
3 (C)	Pick up liner	M3G1	4
4 (D)	Walk to machine liner press tool	W5*2	10
5 (E)	Juggle liner	J2*2	4
6 (F)	Fit liner to press	M4P5	9
7 (G)	Push up liner	M2	2
8 (A)	Move to rack	W5*2	10
9 (H)	Search for green bearing type	E2E2	4
10 (C)	Pick up liner	M3G1	4
11 (D)	Walk to machine liner press tool	W5*2	10
12 (E)	Juggle liner	J2*2	4
13 (F)	Fit liner to press	M4P5	9
14 (G)	Push up liner	M2	2
15 (A)	Move to rack	W5*2	10
16 (I)	Search for yellow bearing type	E2E2	4
17 (C)	Pick up liner	B17 M2G1	20
18 (D)	Walk to machine liner press tool	W5*2	10
19 (E)	Juggle liner	J2*2	4
20 (F)	Fit liner to press	M4P5	9
21 (G)	Push up liner	M2	2
22 (J)	Move to machine control	W5*3	15
23 (K)	Press button to activate press	M4G1 M2P0	7
24 (L)	Walk to engine	W5*3	15
25 (M)	Check five inspecting points	E2*5	10
26 (N)	Make decision	D3	3
27 (O)	Press foot pedal to finish cycle	F3*2	6

Table 4. Process work sequence of Design B
(Size<15mm, α+β≤360, Non-tangling, visible, Holding down required)

	Task	Code	MODs
1 (A)	Move to rack	W5*2	10
2 (B)	Search for orange bearing type	E2E2	4
3 (C)	Pick up bearing liner	M3G1	4
4 (D)	Move liner to other hand	M2G1	3
5 (E)	Search for green bearing type	E2E2	4
6 (C)	Pick up bearing liner	M3G1	4
7 (D)	Move liner to other hand	M2G1	3
8 (F)	Search for yellow bearing type	E2E2	4
9 (C)	Pick up a bearing liner	M4G1	5
10 (G)	Walk to machine liner press tool	W5*2	10
11 (H)	Juggle liner	J2*2	4
12 (I)	Fit liner to press	M2P2	4
13 (J)	Push down liner	M2	2
14 (D)	Move liner to other hand	M2G1	3
15 (H)	Juggle liner	J2*2	4
16 (I)	Fit liner to press	M2P2	4
17 (J)	Push down liner	M2	2
18 (D)	Move liner to other hand	M2G1	3
19 (H)	Juggle liner	J2*2	4
20 (I)	Fit liner to press	M2P2	4
21 (J)	Push down liner	M2	2
22 (K)	Move to machine control	W5*3	15
23 (L)	Press button to activate cycle	M4G1 M2P0	7
24 (M)	Walk to engine	W5*3	15
25 (N)	Check five inspecting points	E2*5	10
26 (O)	Make decision	D3	3
27 (P)	Press foot pedal to finish cycle	F3*2	6

illustrated in Figure 2. In the Design A, the following limitations are identified as the main complexity sources;

- Each pick and fit task requires operator to move back and forth between the rack and press tool.
- The height of the yellow bearing liner tray forces the operator to crouch or kneel and pick the part.
- The press tool has a fixed orientation which impedes the operator's visibility during the fitting of bearing liners.

Design B which addresses these limitations is illustrated in Figure 3 and the work sequence is presented in Table 4. In this design, operator picks all three bearing liners at once, thereby repetitive back and forth movements are avoided. The yellow bearing liner tray is relocated to an ergonomically favourable position so that the operator does not have to crouch or kneel. Moreover, the press tool is redesigned so the operator can fit the bearing liners without vision restriction. Based on these modifications it is hypothesised that Design B will have reduced movement effort factor $E_{i(1,1)}$ as the operator moves to the pick position only once, and reduced terminal effort factor $E_{i(1,2)}$ as the place location is more visible.

The complexity assessment results of both designs are illustrated in Table 5. The presented complexity model indicates an $C_{op,i}$ score 14.7% greater for Design A (10.463) than Design B (9.119). This result demonstrate the effects of design improvements on complexity. Since, the operator has to fit bearing liners to the press tool without clear vision, terminal actions performed in Design A (2.547) have produced a higher terminal complexity $OCI_{i(1,2)}$ (51.4%) score compared to Design B (1.682). This is accurate, because the tasks require high consciousness terminal activities are more complex for operators to perform. Moreover, the effect of design improvements in movement activities can be observed in $OCI_{i(1,1)}$ scores. According to this, the contribution of movement activities in *OCI* has been reduced by 14.5% through eliminating waste movements and unfavourable working postures. Movement complexity scores for Design A and Design B are recorded as 3.780 and 3.301, respectively. Moreover, no change has been observed in auxiliary complexity $OCI_{i,(1,3)}$ scores. As expected, the changes to the design have improved the movement and terminal complexity scores while leaving other factors relatively unchanged. This demonstrates that the model has accurately evaluated the complexity between the designs. Additionally, it is found that cycle times and operational complexity index had an agreement from which a correlation between assembly complexity and assembly time is inferred. This finding is in-line with [14], implying that complex assembly approaches should be avoided to minimise assembly times. Figure 4 represents the comparison between the elements of complexity (i.e. effort, size and diversity) in Design A and B.

Table 5. Complexity assessment results (Design A and Design B)

	Design A			Design B		
$\sum_1^{N_i}\sum_1^{n_{m,j,i}} e_{m,z,j,i}$	14			7		
$\sum_1^{N_i}\sum_1^{n_{t,j,i}} e_{t,z,j,i}$	3			0		
$\sum_1^{N_i}\sum_1^{n_{a,j,i}} e_{a,z,j,i}$	9.5			9.5		
$\sum_1^{N_i} n_{m,j,i}$	30			25		
$\sum_1^{N_i} n_{t,j,i}$	8			12		
$\sum_1^{N_i} n_{a,j,i}$	20			20		
$\sum_1^{N_i} n_{dm,j,i}$	20			19		
$\sum_1^{N_i} n_{dt,j,i}$	8			12		
$\sum_1^{N_i} n_{da,j,i}$	12			12		
$N_{dm,i}$	8			10		
$N_{dt,i}$	3			5		
$N_{da,i}$	7			7		
$N_{m,i}$	18			18		
$N_{t,i}$	7			11		
$N_{a,i}$	9			9		
	Mov	Ter	Aux	Mov	Ter	Aux
E_i (Effort factor)	0.467	0.375	0.475	0.280	0.000	0.475
D_i (Diversity factor)	0.296	0.429	0.467	0.422	0.455	0.467
S_i(Size factor)	4.954	3.170	4.392	4.700	3.700	4.392
OCI_i	3.780	2.547	4.136	3.301	1.682	4.136
$C_{op,i}$ (Total Score)	10.463			9.119		

5. Conclusion and future work

Complexity of assembly operations is an important performance indicator which should be explored and modelled,

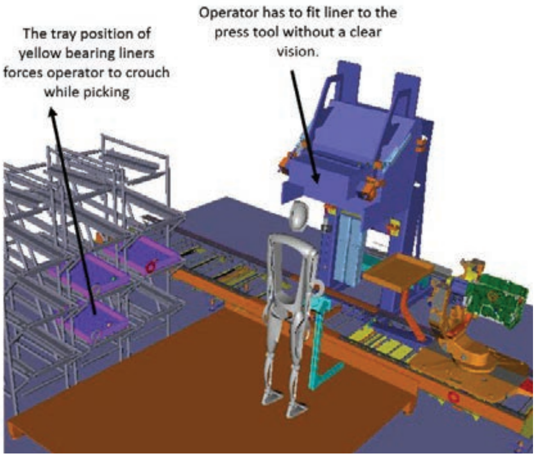

Fig. 2. Design A (initial design)

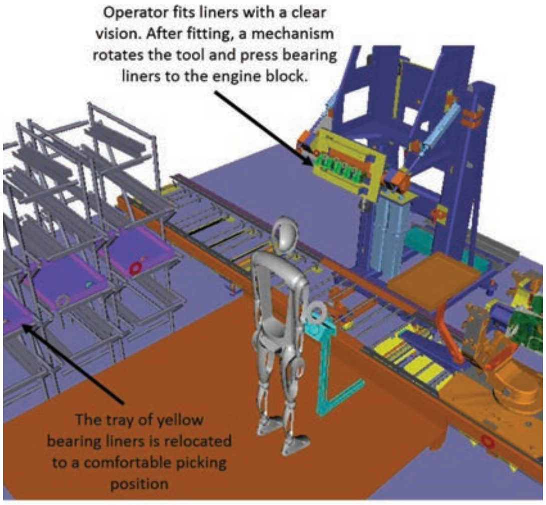

Fig. 3. Design B (slightly optimised version of Design A)

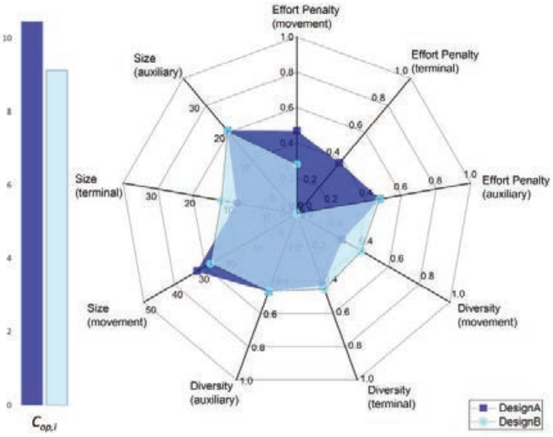

Fig. 4. Comparison of Design A and B: radar chart shows the comparison of different complexity elements, bar chart represents the calculated complexity scores

especially at the early process design stages, to provide optimal working conditions for an operator. This research proposes an operational complexity assessment model and its integration with an existing VM tool. PMTS data is extracted from the vueOne VM tool and used to feed the complexity model. The operational complexity measure considers functions of physical and cognitive efforts, and quantity and diversity of operation related activities. Two different designs of an automotive engine head bearing liner assembly process were used to demonstrate and provide a first-hand evaluation of the proposed complexity assessment method. It was found that the developed model provides an estimate of the operation complexity using solely PMTS descriptions. The authors believe that the proposed method of analysis would help designers assess assembly operation complexity. This could support operation design optimisation and ultimately result in reduced human related failures and assembly risks.

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