

A Virtual Assembly Approach for Product Assemblability Analysis and Workplace Design

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Abstract

A virtual assembly approach is proposed for the analysis of product assemblability during the design stage. A virtual assembly environment created in DELMIA is developed and its capability is demonstrated via a case study of a blower assembly. Based on the simulation of the entire assembly process, cycle time and human factor issues are evaluated from an ergonomics point of view. Comparison results show that the assembly cycle time and energy expenditure can be reduced when the operator posture is improved as a result of workplace redesign. Simulation results of the virtual assembly can be used for the planning and validation of the actual assembly process as well as feedback for design changes.

Keywords:
Virtual assembly environment, Manual assembly, Ergonomics, Workplace design

1 INTRODUCTION

To enhance competition in the global market, manufacturing companies are increasingly concerned with product and process validation in order to facilitate efficient and effective engineering changes [1]. Assembly process validation is an area that needs special consideration due to its direct influences on product quality, time to market and cost [2]. The minimization of the product cycle time and work induced fatigue are two significant factors during validation. Therefore, it is beneficial to incorporate a complete ergonomic analysis of the assembly process for a new product design.

In the late 90s, ergonomic analysis was mostly supported by videotaping systems, i.e. a videotape of an operator performing the assembly operations [3-5]. Such research analyzed the videotape of work methods and workplace layout. With the development of computer hardware and software, 3D simulation techniques were employed in ergonomic analysis. Generally, information on assembly sequence, operator movements, etc. from the workplace is collected and then a virtual manufacturing environment mimicking the actual physical environment is constructed. Iterative simulations can be conducted in such a virtual environment for ergonomic analysis [6-8]. However, such analyses are often based on an existing product and workplace. The construction of these physical prototypes will increase product development lead time and costs. Therefore, there are significant advantages in the concurrent study of human factors for product assembly during the design stage.

Chryssolouris et al. developed an experimental virtual environment for the verification of manual assembly processes [9]. An immersive virtual environment with a CyberGlove was used in their study of four alternative layouts for the assembly of a boat propeller. The influence of a number of process parameters and their combinations on the process cycle time were also quantified. Rajan et al. developed a Virtual Reality-based environment JIGPRO for aircraft floor assembly jig design and analysis [10]. 3D CAD models of assembly product, jig and a virtual hand were imported into JIGPRO for assembly process simulation and accessibility analysis. The main purpose was to analyze accessibility during assembly and to evaluate the risk of musculoskeletal injuries. Sundin et al. described a case study of bus chassis assembly which aimed to improve efficiency and ergonomics in the early design stages [11]. 'Jack' was used for the construction of a computer manikin and ergonomic analysis of different work sequences including posture was conducted.

This investigation demonstrates the capability of a virtual assembly approach in product assemblability analysis and workplace design based on a blower assembly case study. A virtual assembly environment is created and a digital human model is introduced to perform all necessary assembly operations. Three metrics are used in this study: operator posture, energy expenditure and process cycle time. They are evaluated and used for the redesign of the workplace in this phase of virtual assembly.

2 METHODOLOGY

2.1 Virtual assembly environment

DELMIA V5R20 is adopted for the creation of virtual assembly environment and process simulation. Its digital manufacturing approach is built upon a Product, Process, and Resource (PPR) model providing a central hub connecting all relevant data as shown in Figure 1. Especially, its virtual ergonomics provision offers a digital human modeling capability for the creation, validation and simulation of operator/product interaction. The digital operator can perform activities such as walk to a specific location (across floors, up ladders, down stairs) based on time parameters defined by the user, move from one target posture to another, as well as pick and place parts in the work area by following the movements and paths of objects. These activities can be combined with assembly activities
for the analysis of the relationship between operators and other entities in simulation. Generally, operator activities can be defined by three different methods. Firstly, defined by standard activities, such as walk, climb the stairs and climb the ladder. However, only a limited number of standard activities are available in DELMIA. Secondly, defined by adjusting the freedom of a segment. A digital human model in DELMIA has 68 segments. They all have their own degrees of freedom, which is usually 2 or 3. By regulating the degree of freedom of a segment, specific operator posture can be defined. Finally, the third method is via inverse kinematic. When the path of an object is defined, the operator’s hand can follow this specific path in space. Meanwhile, there are 5 inverse kinematic control points in DELMIA which are line of sight, pelvis, right hand, left hand, right foot and left foot. Users can assign specific locations for these points in space and corresponding posture of the operator can be obtained through inverse kinematic.

A complete virtual environment allows the preparation and inputs of all digital models involved in assembly process. These include component 3D models, workplace models, materials storage models, tool, fasteners and an operator model. These models should be loaded and located in the virtual assembly environment.

Within the virtual assembly environment, a rapid analysis for assembly process can be conducted. The product assemblability in terms of performance metrics such as RULA scores (cf Section 2.2), assembly process cycle time and the energy expenditure of the operator can be estimated. Such analysis can be part of an approach for a single or multi objective optimization. An overview of the virtual assembly environment simulation is shown in Figure 2.

Figure 1: PPR model in DELMIA.

![Diagram](image_url)

Figure 2: The simulation flow chart of the virtual assembly environment.

### 2.2 Analysis methodology

#### RULA score

The RULA (Rapid Upper Limb Assessment) system was developed to investigate the exposure of individual operators to risks associated with work-related upper limb disorders [12]. An RULA analysis examines the following risk factors: number of movements, static muscle work, force, working posture, and time worked without a break. All these factors are combined to provide a final score that ranges from 1 to 7:

- 1 and 2 – Indicates that the posture is acceptable if it is not maintained or repeated for long periods of time.
- 3 and 4 – Indicates that further investigation is needed and changes may be required.
- 5 and 6 – Indicates that investigation and changes are required soon.
- 7 – Indicates that investigation and changes are required immediately.

#### Process cycle time

A functional timer enables the user to record the process time of each individual step of the assembly process. Manual assembly can be divided naturally into two components, handling (acquiring, orienting and moving the parts), and insertion and fastening (mating a part to another part or group parts) [13]. Thus, the total assembly process time $t$ is calculated as:

$$ t = t_h + t_i $$  \hspace{1cm} (1)$$

Where $t_h$ = handling time

$$ t_i = \text{insertion and fastening time} $$

#### Energy expenditure

GARG equations are empirical metabolic energy predictive equations. They are adopted for energy expenditure calculations in this investigation as shown in Table 1 [14]. It assumes that an assembly task can be divided into simple basic operations. Once this step has been applied, the average rate for the entire job (in kcal/min) can be estimated by summing up the energy requirements for each individual operation and the energy required to maintain the posture.
GARG equations

For stoop lift:

\[ E = 0.0109 \times BW + (0.0012 \times BW + 0.0052 \times L + 0.0028 \times S \times L)F \]

For squat lift:

\[ E = 0.0109 \times BW + (0.0019 \times BW + 0.0081 \times L + 0.0023 \times S \times L)F \]

For arm lift:

\[ E = 0.0109 \times BW + (0.0019 \times BW + 0.0081 \times L + 0.0023 \times S \times L)F \]

Where

- \( E \): energy expenditure (kcal/min)
- \( BW \): body weight (lb)
- \( S \): gender (female = 0, male = 1)
- \( F \): lifting frequency (lifts/min)
- \( L \): load weight (lb)

Table 1: Energy expenditure calculation in virtual assembly environment.

### 3 CASE STUDY

As a demonstration of the capabilities of the virtual assembly environment, a case study of an aluminum blower assembly was carried out. The blower, as shown in Figure 3, was designed for remote control model aircraft applications [15]. The heaviest part of the blower is the housing which has a mass of 5.695 kg. The assembly process consists of five tasks: 1) crankshaft assembly; 2) piston sub-assembly; 3) piston assembly; 4) housing assembly; 5) impeller assembly. Each task requires the operator to acquire parts from the storage bench, transport them, and fasten them in a fixed location on the workbench. The digital operator is based on a 50 percentile US male as provided within the DELMIA database. The operator has a height of 175.58 cm and weighs 78.49 kg. The virtual assembly environment constructed for this case study is given in Figure 4 and the individual steps of the assembly process are shown in Table 2. The objectives of this case study are:

- to predict and evaluate ergonomic issues during assembly process;
- to model the assembly cycle time and energy expenditure;
- to improve assembly cycle time and energy expenditure via workplace redesign.

![Figure 3: Blower model for assembly [15].](image)

![Figure 4: The virtual assembly environment.](image)

<table>
<thead>
<tr>
<th>Task</th>
<th>Handling</th>
<th>Fastening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crankshaft assembly</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>Piston sub-assembly</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
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<tr>
<td>Piston assembly</td>
<td><img src="image" alt="Image" /></td>
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<tr>
<td>Housing assembly</td>
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<tr>
<td>Impeller assembly</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
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</table>

Table 2: Assembly process of the blower.
4 ANALYSIS

4.1 RULA analysis

A propagation of the assembly task’s RULA scores along the process time is given in Figure 5. There is only one RULA score at any instant and it is updated for each 0.1 sec interval. For this operation, the highest RULA score 7 appears in the crankshaft assembly operation. This sends a strong signal that changes must be made to this task immediately. The sequences of operator posture for this task are shown in Figure 6. It is evident that in order to insert the crankshaft into the engine block, the operator is squatting and the upper body is leaning and stooping. These postures impose stress and fatigue for the operator. With such knowledge, it is logical to hypothesize that a new and less stressful posture could be attained if the workbench is higher.

Based on this observation, the workplace layout was redesigned by increasing the height of the standard workbench from 70 cm to 90 cm. After the workplace design modification, a detailed ergonomic simulation was performed again and the new RULA scores for the assembly tasks are shown in Figure 7. For the new workplace design, the RULA score 7 in the ‘danger’ zone is totally eliminated. Further, the stressful posture of squatting is removed and other postures are also improved with the new operator posture as illustrated in Figure 8.

4.2 Process cycle time analysis

The original assembly cycle time $t_0$ is 213 sec. After workplace redesign, the new cycle time $t_1$ is reduced to 204 sec. The total cycle time is reduced by 4.2% simply by workbench height adjustment. An overall comparison of each assembly task for the two simulations is given in Figure 9. It is evident that 3 out 10 assembly tasks, i.e., crankshaft fastening, housing fastening and impeller fastening, show a reduction in assembly time while there are no changes for other operations. In this case study, the assembly cycle time reduction is attributed to the removal of the undesirable and stressful posture of squatting as a result of workplace redesign.

4.3 Energy expenditure analysis

As the process cycle time was reduced by 4.2% after the workplace redesign, the total energy expenditure was also reduced. Moreover, based on the GARG equations in Table 1, the energy expenditure per min of arm lift is lower than stoop lift and squat lift when other parameters, i.e. the body weight, operator gender, lifting frequency and load weight remain unchanged. Consequently, the energy expenditure will decrease correspondingly when the squat and stoop movements are reduced. As the energy expenditure related to the original workplace was 8.951 kcal and the result for the redesigned workplace layout was 8.544 kcal, the reduction in energy expenditure amounted to 4.5%. This change will contribute to an improvement of the overall operator performance.

5 CONCLUSION

A virtual assembly approach is proposed for the analysis of product assemblability. In this investigation, a virtual assembly environment was developed and an assembly cycle time and an energy expenditure calculation model were embedded into this environment. A case study of assembling a blower for a remote control model aircraft...
application is employed to demonstrate the capability of this virtual assembly environment. The entire assembly process simulation consists of four assembly tasks and one sub-assembly task. Human factors were evaluated and a new design of the workplace is proposed based on the ergonomic problems identified in the assembly process. Simulation results show that the assembly cycle time and energy expenditure can be reduced through an improvement of the operator’s posture. The process cycle time and energy expenditure can be reduced by 4.2% and 4.5% respectively. Further simulations could be made to optimize individual metric or a combination of them. Results obtained from the virtual assembly analysis can also be used for process validation and verification before actual production.

6 ACKNOWLEDGMENTS
This work was supported by the Northwest Regional Development Agency and the European Regional Development Fund.

7 REFERENCES