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AN APPROACH FOR IMPROVING MAINTAINABILITY PERFORMANCE OF MECHANICAL COMPLEX PRODUCTS AT EARLY STAGES OF DESIGN PROCESS

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Advisors: Professor Carlos Cziulik, Ph.D. and Professor Paulo André de Camargo Beltrão, Ph.D.

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RESUMO

Embora a mantenabilidade seja um parâmetro importante no Processo de Desenvolvimento de Produto (PDP), entende-se que a manutenção não é devidamente considerada no desenvolvimento. A dificuldade aumenta em produtos mecânicos complexos onde existe pluralidade de interfaces com diferentes grupos de engenharias. Na revisão bibliográfica, enquanto a literatura clássica está distante do desenvolvimento real porque raramente discute o PD em ambientes virtuais, outros novos estudos de diferentes periódicos propõem algorítimos matemáticos impraticáveis ou análises de mantenabilidade virtuais altamente dependentes de especialistas neste parâmetro. O objetivo da tese foi propor um modelo e técnicas associadas (diretrizes) para aprimorar a análise do parâmetro de mantenabilidade durante o desenvolvimento virtual no PDP. O modelo desenvolvido foi implementado na forma de um plug-in, em um software de CAD comercial, com uma função para rastrear componentes importantes para o pós-venda e outra para avaliar automaticamente o acesso a elementos de fixação destes produtos. A proposta apresentada foi verificada e validada em quatro contextos diferentes a saber: i/ verificação de funcionalidades; ii/ contraste com a proposta de Popescu and Iacob (2013); iii/ comparação com o plug-in de Junior (2015); iv/ verificação e coleta de dados com um grupo de engenheiros de desenvolvimento. Com base nos resultados obtidos pode se inferir que o modelo auxilia o engenheiros de desenvolvimento a melhorar a aplicação do parâmetro de mantenabilidade sendo menos dependentes de especialistas nesta área. Conclusões da pesquisa e propostas para suportar futuros estudos são ofertadas.

Palavras-chave: Mantenabilidade, Desenvolvimento de Produto, CAD

MOSCHETO, A. D., **An Approach for Improving Maintainability Performance of Mechanical Complex Products at Early Stages of Design Process**. 2017. 241 p. Thesis (Doctorate in Engineering) – PPGEM, Federal University of Technology - Paraná State, Curitiba-Brazil (in English), 2017.

ABSTRACT

Although maintainability is regarded as an important parameter during Product Development Process (PDP), it is believed that the product maintenance is not properly considered by the development engineers. The difficulty further increases in complex mechanical products where a plurality of interfaces with different design groups exists. During the literature review, while classical literature is distant of real product development because it barely discusses PD in virtual environments, other newer studies from different sources propose impracticable mathematical algorithms or highly dependable virtual maintenance analysis based on expert's knowledge in order to address such parameter. The thesis objective is to propose a model and associated techniques (directives) to improve maintainability parameter analysis during the virtual development in PDP. The proposed model was implemented in a plug-in format, in a commercial CAD software, with one function to track important aftermarket components and another to automatically evaluate fasteners access on such products. The proposed model was verified and validated in four different contexts: i/ functionality verification; ii/ contrast with Popescu and Iacob (2013) proposal; iii/ comparison with Junior (2015) plug-in; iv/ verification and data collection with a group of development engineers. Based on the obtained results can be inferred that the model assists the development engineers to improve the application of the maintainability parameter being less dependent on the area specialists. Research conclusions and proposals to support future studies are offered.

Keywords: Maintainability, Product Development, Computer Aided Design

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LIST OF ABBREVIATIONS & ACRONYMS

AHP	Analytical Hierarchical Process
CAD	Computer Aided Design
DFA	Design for Assembly
DFMT	Design for Maintainability
EOL	End-of-Life
FMECA	Failure Mode, Effects, and Criticality Analysis
IMMA	Intelligently Moving Manikins
IPS	Industrial Path Solutions
KBE	Knowledge-based Engineering
MTTR	Mean Time To Repair
PD	Product Development
PDP	Product Development Process
RULA	Rapid Upper Limb Assessment
VH	Virtual Human
VR	Virtual Reality
WP	Wave Propagation Method

CONTENTS

1 INTRODUCTION

In this chapter, the motivation for this thesis proposal is presented, highlighting the importance of correctly addressing maintainability parameter within Product Development Process (PDP). Opportunity characterization, objectives, expected results as well as justification for this research are listed. Finally, the thesis proposal structure is offered.

1.1 Research motivation

Profit margins of different companies can be hindered on their product sales with the current competitiveness levels reached on a globalized world economy. This fact, forces corporations to invest even further on Product Development (PD) trying to create a portfolio with new products or even to enhance current products' features. Hajej, Tutki and Rezg (2015) confirm this scenario mentioning that over the last decades companies have to cope with reduced profit margins due to highly competitive environments, motivating them to seek improvement in their maintenance and production planning.

Highly regarded companies produce 75% of revenue from their new products/services that did not exist five years earlier (KUMAR; KHAN; GANDHI, 2011). Thus, in order to improve and/or generate new products, business companies need to apply Product Development Processes (PDP) to minimize the chances of not properly developing their new ideas, and by that, reaching the market with a higher chance of delivering successful products.

To develop a product as it used to be approached before, with focus on manufacturing only, is no longer the case (SMITH, 1997). For Coubalibaly, Houssin and Mutel (2008) current product development processes have reached the limit. Therefore, companies must improve their knowledge about environmental matters and products' life cycle if they want to generate new competitive advantages.

Popescu and Iacob (2013) add the fact that manufacturers are dealing with new regulations concerning end-of-life (EOL) issues such as recycling and reuse of their products. It can be quite time consuming and therefore costly to disassemble a product if an inefficient disassembly design is applied for a product (SOH; ONG; NEE, 2016).

Zhou *et al.* (2016) assures that life cost of products can be reduced and maintainer comfort can be improved if maintainability parameter is well addressed. There are several aspects of a product life-cycle which normally could not be correctly examined along PDP. Figure 1.1 shows the “Iceberg effect” in which several hidden costs are presented. Blanchard, Verma and Peterson (1995) say that up to 75% of long-term costs, related to the useful life of a certain product, are not addressed in PDP. One of these hidden costs, not properly considered along PDP and, which is the focus of this thesis proposal, is the Maintenance Cost.

Unfortunately, maintenance may be seen *“in industry as a necessary evil, an expense or loss which the organization must incur to keep production process operative. Because of this, the priorities of a company do not typically focus on maintaining assets, but on the production that they represent”* (KUMAR *et al.*, 2013).

Maintenance costs are directly connected to:

a) Amount of time spent in order to restore the system to its original operational condition. Low reliability and poor maintainability (accessibility, visibility, reachability, operation space, and ergonomic design) in a product causes frequent breakdowns with long downtimes. Therefore, maintainability and maintenance strategies have high impact on product availability (JOLLY; SINGH, 2014);

b) Product complexity: demands highly skilled personnel to fix it;

c) Product support: logistic support, spare parts, necessary tools, among others;

d) Product time loss: the longer the product is being fixed, less productivity it delivers.

For large-scale systems maintenance costs can be as high as 60 to 75% of life cycle cost (KUMAR; KHAN; GANDHI, 2011). Also, on complex systems, maintenance and inspection deficiencies are considered important factors that can lead to accidents and failures (HE *et al*., 2016).

According to MIL-HDBK-470A (1997) the objective during research and development should be to reduce as much as possible life cycle costs. To that end, Sharma, Yadava and Deshmukh (2011) affirm that Maintenance is becoming a profit generating business and, therefore, the correct application of maintainability as a design parameter throughout PDP is a key activity to create successful products in the market. Maintainability has to be considered as a critical factor in the economic success of an engineering product (DONG; LE; CHUAN, 2013), as "*maintenance plays an important role in sustaining and improving asset availability, which in turn affects the productivity of the system in interest*" (ALRABGHI, 2015). Creating an ease to maintain product is an important factor to gain customer loyalty, as customers recognize a good quality product also by its maintainability quality.

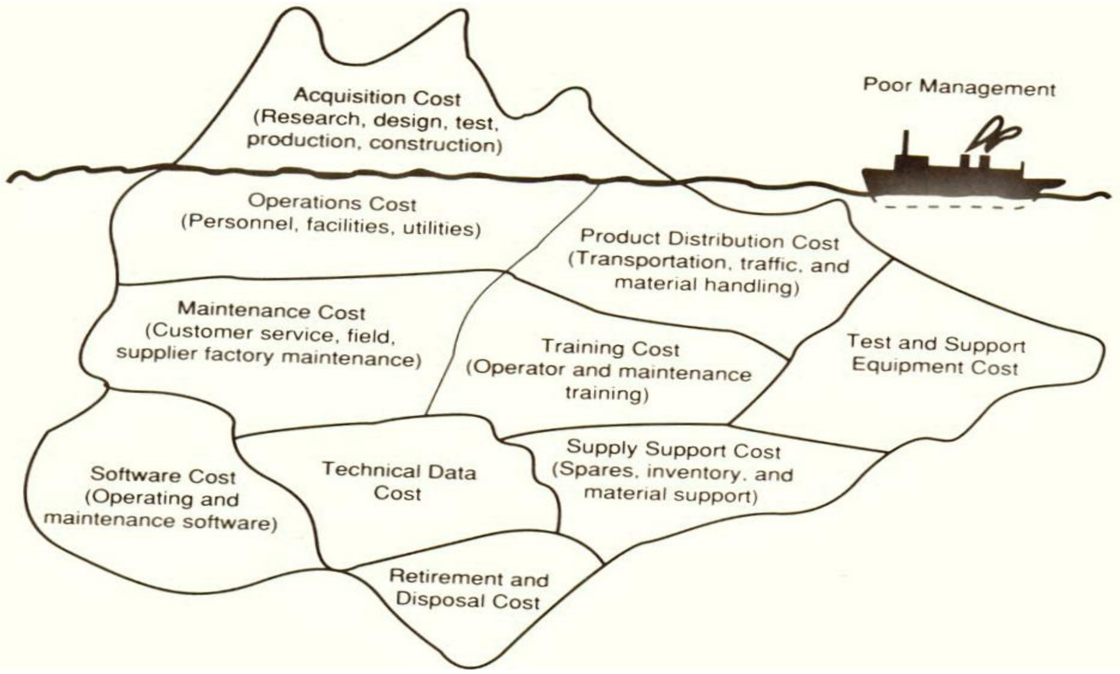

Figure 1.1 – Visibility of a product's total cost[1]
Source: Adapted from Blanchard, Verma & Peterson (1995).

Then, if Maintenance is an important factor in PD, why is it not properly addressed at this stage? Spite of being highlighted by Blanchard and Fabrycky (2006), Rozenfeld et al. (2006) and Pahl and Beitz (1996), by briefly introducing the importance of including maintainability as a design parameter with some directives and indicators (e.g. MTTR), it is not clear how to approach the topic during product development, as

[1] All figures and tables where the source is not presented were produced by the Ph.D. candidate.

far as manufacturing is concerned nowadays. In other words, despite recognizing the importance of such matter, the literature brings no adequate subsidies to guide a product development engineer towards the understanding and means necessary to deliver such maintainability demands/expectations, from the conceptual phase, and to ensure they are adequately included in the final product. Maintainability requirements are quite often emphasised on maintenance frequencies and time duration, while human aspects are normally ignored (BLANCHARD; VERMA; PETERSON, 1995).

Another question that arises is when, in PDP, such parameters must be examined, since the classic methods for product development have superficially considered the matter. In general all topics related to product support (including maintainability) are explored too late, in project phases where conceptual alterations would be practically impossible (MARKESET; KUMAR, 2003).

The same classical literature barely discuss how developments in virtual environments should take place as well. As nowadays, it is nearly impossible to think about PDP without considering CAD systems, this is another motivation for this study.

As a significant percentage of products availability is tightly connected to how maintainability parameter has been encompassed within PD, an important challenge for companies when using virtual development is to structure a clear strategy in order to be more efficient when designing their products (BODEIN; ROSE; CAILLAUD, 2013).

On practical basis, there is a big gap in communication and knowledge between experienced field engineers/technicians and the development team (including CAD specialists). This is confirmed by MIL-HDBK-470A (1997) which declares: "*Designing equipment that is easy to operate, assemble, and* ***maintain*** *is often hindered by poor communications between the design team and personnel familiar with the operation, assembly, or* ***maintenance*** *of similar or existing equipment"*. Normally, field engineers do not have the time as well, to support engineers with necessary reviews and tips to improve product development.

Therefore, this thesis proposal considers the following research questions: what are the methods/tools currently in use to address maintainability parameter along PDP? Are they truthfully connected to real life product development by being user friendly? How to support the knowledge shift from field personnel to development team to enhance product maintenance? How to propose a method/tool which minimizes the dependence of experience, and guides design engineers to develop better complex products[2] under maintainability scope?

1.2 Opportunity identification and characterization

Sharma, Yadava and Deshmukh (2011) have performed an extensive research on maintenance optimization. One of their major conclusions is that there exists a wide gap between theory and practice. In other words, studies conducted are far away from the real product development, making it harder to take advantage of research findings into real life development challenges.

Looking at the maintainability parameter perspective, the key question to be examined during PDP then is how long it will take to restore and/or maintain the product in its original functionality. To answer this question, several factors may be used to justify the product uptime level, such as: i/ accessibility to the component to be replaced (e.g. Figure 1.2); ii/ component mass (ergonomic related); iii/ diagnosis easiness; iv/ usage of universal or special tools; v/ availability of spare parts; among others.

Figure 1.2 – Difficult access
Source: Moscheto (2009)

To reach the desired uptime level some major blockages are foreseen. Historically maintainability parameter has been considered common sense in PD (MIL-HDBK-470A, 1997). Thus, there exists a considerable knowledge barrier between the product development engineer and the field engineer (ZIMMERMAN; BERGSJÖ; MALMQVIST, 2006) and that on maintenance analysis experience is extremely vital

[2] As per Geng *et al.* (2014), "*Complex products mostly have complicated product structure, large number of parts with very different shapes, compact spatial structure and layout*". Examples of complex products are heavy-duty vehicles, aircraft, vessels, automotive vehicles in general. According to the authors these type of products normally have a life span of over ten years.

(GENG, *et al*., 2013). Therefore, how this field knowledge could be converted to less experienced designers in their normal working environment in CAD Systems?

Thus, it is clear that there exists a knowledge gap in the development team that may be covered by simultaneous engineering (joining different department expertise in design reviews) or by trying to improve the way engineering designers create their concepts in virtual tools.

From that, it is relevant to broaden the knowledge, within Product Development Process, so that maintainability can be better investigated. As it is a project parameter directly related to customers' satisfaction and as the actual literature provides no consistent guidelines on the necessary actions so that the matter is dully addressed during PDP, there are several different possibilities to extend the scientific knowledge in this area. To structure a model and tool that minimizes the demand for empirical knowledge, supporting designers to correctly create new product solutions in virtual systems counting with maintainability parameter tips, could reduce reworks and help to reach maintenance project goals (e.g. MTTR), being then widely welcome by development teams.

1.3 Objectives

The thesis objective is to propose a model and associated techniques to improve maintainability parameter analysis during product development process. Such model shall support designers to correctly address maintainability parameter in their common development environment – computer aided design.

As today the majority of PD occurs on 3D CAD systems, such model should be created/applied on a plug-in tool integrated in a CAD system. The idea is to better guide product development in virtual environments, focusing on maintenance, and to automate key-components fasteners' access analysis, reducing the level of experience dependency on this design parameter.

Note: the model is to be structured as proof of concept, using a controlled test environment with a pre-defined case study only. Even though, a plug-in shall be created/programmed in a CAD system, the fundamental objective of the proposed thesis is to evaluate how well the envisaged model is accepted by different designers on a controlled test environment focusing on maintainability aspects only[3].

1.3.1 Specific objectives

To support the thesis research and serve as specific objectives is important to:

a. Understand how mechanics evaluate fasteners' removal movements;
b. Investigate fasteners removal barriers possibilities in order to create a proper environment for fasteners' access analysis using the developed plug-in;
c. Create a solution to minimize the area of analysis when evaluating fastener access leval in a mechanical complex product;
d. Include ergonomical aspects in the fasteners' access analysis.

1.4 Reasoning

Besides providing product development engineers with more specific subsidies to work with maintenance aspects, it is desirable that products developed via the proposed model tool will be simpler and restored to their original functioning status in the shortest time possible using the minimum number of universal/special tools.

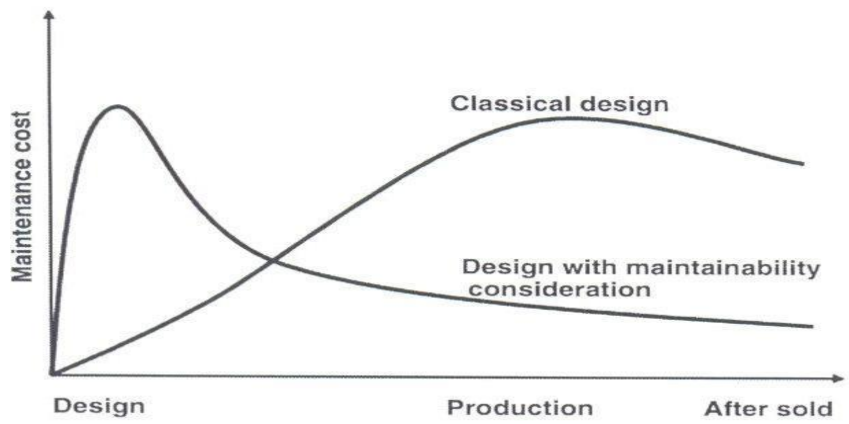

Figure 1.3 – Development taking into consideration maintainability.
Source: Slavila, Decreuse and Ferney (2005).

Products developed by the help of such approach shall improve customers' satisfaction in the aftermarket, reducing maintenance costs along products life-cycle

[3] It is not the objective of this research to evaluate different programming languages, processing times, different algorithms possibilities, and/or create extense library databases for universal tools/ergonomic access analysis.

(see Figure 1.3). Companies shall increase their incomes if they include this maintainability analysis during product conceptual development.

To reinforce the importance of addressing maintainability in the right moment, the MIL-HDBK-470A standard (1997) states that this parameter has to be considered in the design, as any attempt to improve maintainability after the product development *freezing point* will be expensive and inefficient.

By applying Design for Maintainability, customers will benefit from less downtime, lower maintenance costs, reduced number of tools, smaller inventory, safer products, among other advantages (PENG *et al.*, 2012). By influencing the way designers behave towards maintainability during conceptual and preliminary development phases will generate several benefits:

a) Improved corrective and preventive product maintenance;

b) Service operations standard time reductions;

c) Simpler products, meaning less knowledge level to repair it, as well as, rationalized level of inventory (standardization);

d) Better access/inspection to key-components with less tools (universal and special tools);

e) Reduced level of reworks due to maintainability improvements request on design reviews.

In the end, all benefits stated above will bring higher gains on customer loyalty and increase of companies' income.

Therefore, further research on maintainability will provide new pieces of information on how to apply this parameter during PDP, adding to the current literature, and helping people connected to PDP, understand and apply such relevant parameter.

1.5 Research methodology

This investigation involves a theoretical-practical approach. The methodology applied is defined as exploratory research. The thesis was based firstly on a literature review. Then, a maintainability model was suggested, explored with different test-cases scenarios by the researcher, and finally applied in interviews with development engineers (with practical experience). The techniques employed during the interviews were the usage of case studies, writing questionnaire answers from the participants and observations performed during the test-case interviews application. Qualitative and quantitative data were collected from the research

The work is also considered to be an Applied Research, as it will be meant to generate knowledge for practical applications, focusing on the solution of a specific problem – to establish a model to improve the maintainability parameter application during PDP.

1.6 Thesis proposal structure

Thesis proposal is structured in five different chapters.

Chapter 1 brings a brief introduction on maintainability parameter, and why is important to address it (research motivation) along PDP through a new model and related technique to be developed as final objective on this study.

Next chapter explores available literature to present classic and new approaches of applying maintainability parameter in the development cycle. Discussions on the current gaps are brought in order to make clear what is actually missing in the current maintainability literature.

A maintainability model and proposal of study is presented on chapter 3 aiming the automation and/or guidance of designers on maintainability analysis. A plug-in implementation is fully described. Its functionalities are explored.

On chapter 4 case studies are brought in order to illustrate real design scenarios and how the proposed model can be applied to help new products to achieve reasonings mentioned on section 1.4. A verification and validation performed with engineers with different experience levels is presented.

Chapter 5 brings research conclusions and proposals to support future studies.

2 MAINTAINABILITY CONSIDERATIONS DURING PD

2.1 What is maintenance?

As stated on Figure 1.1, Maintenance is one of the life cycle costs of a product. According to Pahl and Beitz (1996), systems and/or products are subject to wear and tear, corrosion, contamination and alterations in the properties of the materials. After a certain period, being used or not, the product's condition may not be the desirable one anymore. Thus, to restore the product to its original status or to maintain its operational condition, a set of actions and resources are necessary. Such set is called maintenance.

As for maintainability, it is a design parameter (MIL-HDBK-470A, 1997). During Product Development maintainability parameter aims to enhance product maintenance, by assuring faster repair times with the minimum level of resources and personnel skills possible, and by guaranteeing proper ergonomic conditions.

Maintenance is typically classified as preventive and corrective (GULLEGE; HIROSHIGE; IYER, 2010) - Figure 2.1. A corrective maintenance's objective is to restore the product to its operational condition after a breakdown (failure occurrence). Preventive maintenance seeks to perform services in pre-defined intervals, aiming at keeping the product operational status at a required level.

The preventive maintenance is divided into programmed and controlled maintenances. The programmed maintenance is carried out as a pre-set intervention program, whereas the controlled maintenance also called predictive uses analytic techniques, by means of centralized supervision or sampling, which can more precisely set the correct moment to execute the maintenance with no availability loss (PALLEROSI, 2007).

Both maintenance types are directly related to the downtime period in a product life cycle (Figure 2.2). The downtime is highly impacted usually by the access level of a component to be maintained. This is confirmed by Dhillon (1999) who uses a US Army common standard to define the importance of accessibility in product development: "*to access a piece of equipment is, probably, the second most time-consuming task; second only to failure isolation, and if there is an automatic failure* *detection system available, access is certainly the most time-consuming task".* Popescu and Iacob (2013) confirm the importance of the disassembly process, which influences recycling, maintenance, repair and component/material re-using (essential aspects of sustainable development).

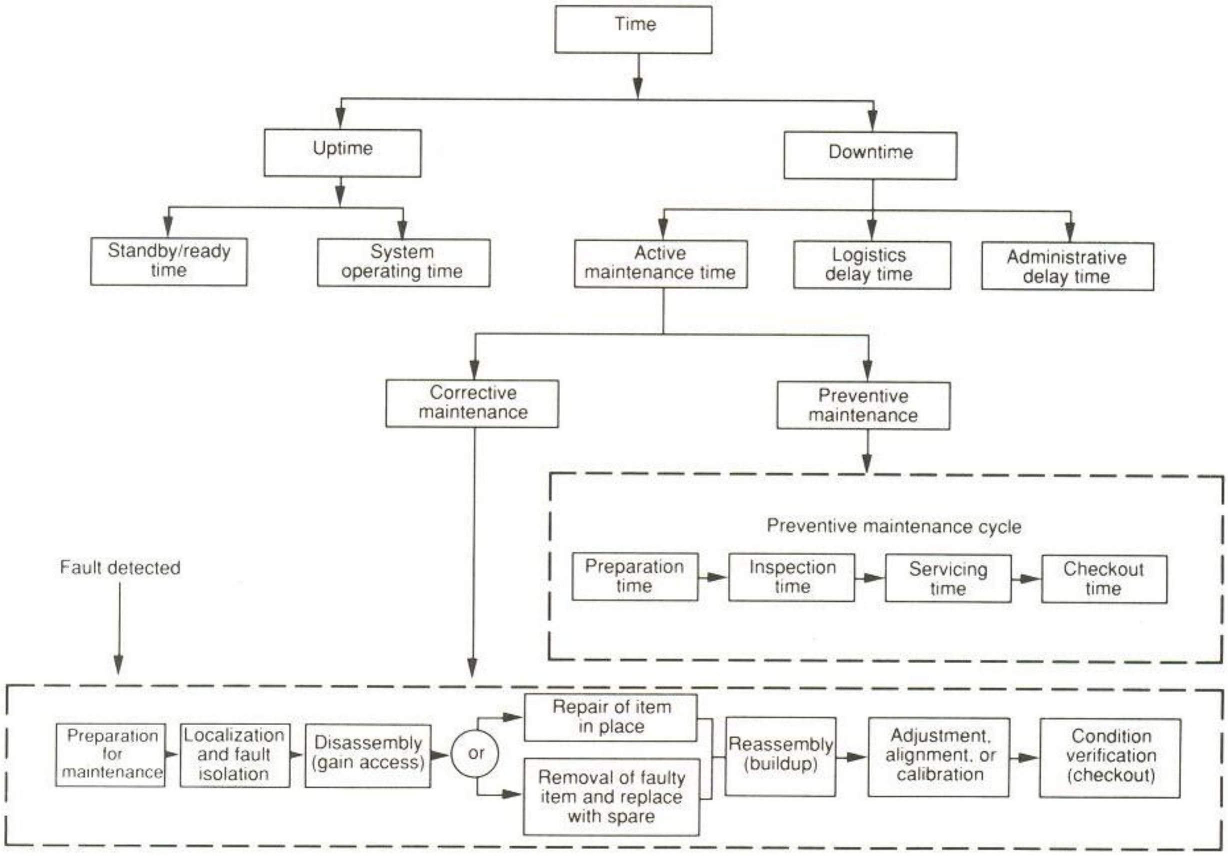

Figure 2.1 – Availability and types of maintenance.
Source: Blanchard, Verma and Peterson (1995).

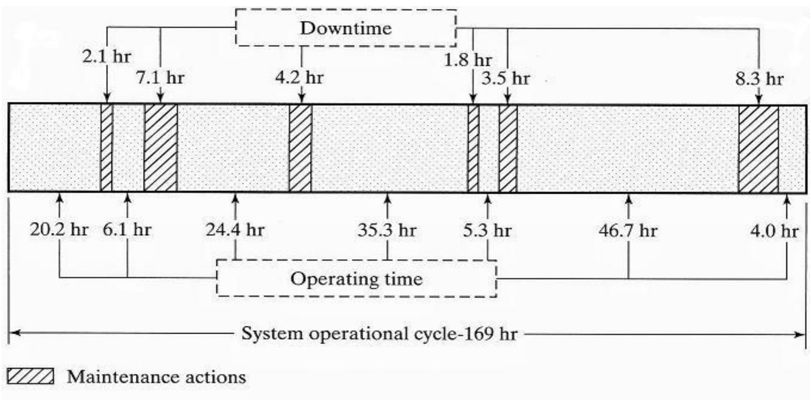

Figure 2.2 - Availability / unavailability concept
Source: Blanchard and Fabrycky (2006).

Apart from access level, maintenance may also be impacted by the environment in which service actions are going to occur and by the spare parts repair policy defined by the manufacturer. These are important life cycle aspects that must be considered in the maintainability analysis during PDP.

2.2 Maintainability in product development process

A process to develop a product is normally required to convert an idea in to a successful product in the market. In spite of the variations, from author to author, in the number of phases (e.g. Figure 2.3) and/or in the composition of each one of them, basically, it is possible to say that PDP's kernel is the same. It starts with the transformation of customers' needs (after a market survey) into the specification of a product (e.g. with the help of House of Quality). With that, the essential problems are declared - in order to compose the product's functional structure. From this structure several different alternatives are generated, aiming at solving the existing problems (e.g. use of brainstorming and morphologic matrix). So, after assessing the generated alternatives (e.g. use of absolute assessment matrix), the development team chooses the concept to deepen and detail the project until the expected final product is reached (MOSCHETO, 2009).

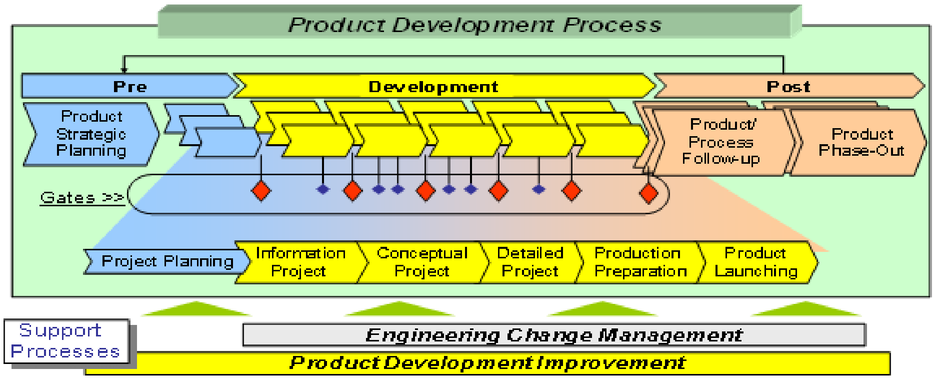

Figure 2.3 - Product Development Process
Source: Rozenfeld *et al.* (2006).

In order to reach a good maintenance level, maintainability parameter needs to be correctly addressed throughout the PDP. However, as the designer is strongly influenced by several others inputs (e.g. manufacturing) coming from different sectors within the company (ZIMMERMAN; BERGSJÖ; MALMQVIST, 2006), it may not be easy to convince the organization to attend such demand in a limited resource with time pressure project environment.

Thus, it is important to understand how well this parameter is presented in the classical literature, in order to comprehend the timing and how it should be applied along the PDP.

Blanchard, Verma and Peterson (1995) have written a complete book focusing on maintainability. On Figure 2.4 these authors present the maintainability tasks to be accomplished throughout a product life cycle. They emphasise the usage of maintainability tools (e.g. FMECA) and maintainability analysis by applying check-lists for instance. However, it is not clear how the goals proposed on the quantitative and qualitative requirements under conceptual design phase will be converted into the final product. Due to the time the book was written, very little is said about the application of CAD systems.

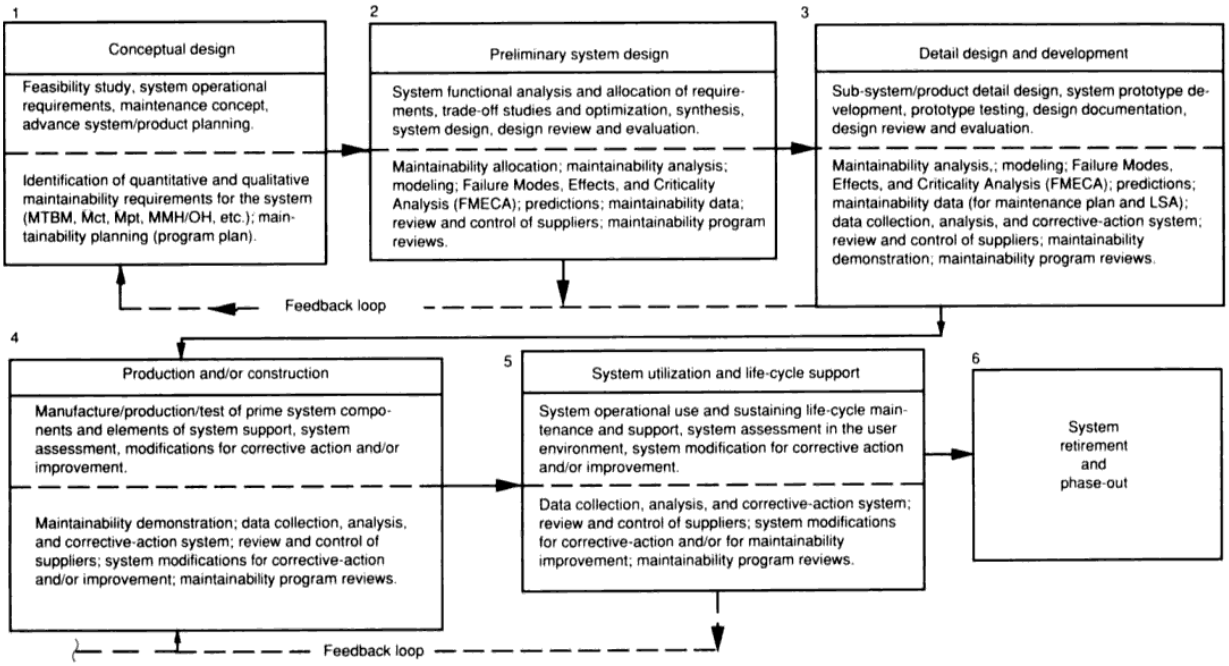

Figure 2.4 – Maintainability in the system life cycle
Source: Blanchard, Verma and Peterson (1995).

Next, there is a complete review made on Pahl and Beitz (1996) from the maintainability's point of view. These authors declare that besides satisfying the functionality and the inter-relationship between components, a solution that observes aspects of maintainability must also be ensured, guaranteeing the conservation and the possibility of inspecting and repairing the product. They advise to consider earlier this parameter, in the conceptual phase, at least in its essence.

Pahl and Beitz design phases are expressed on Figure 2.5.

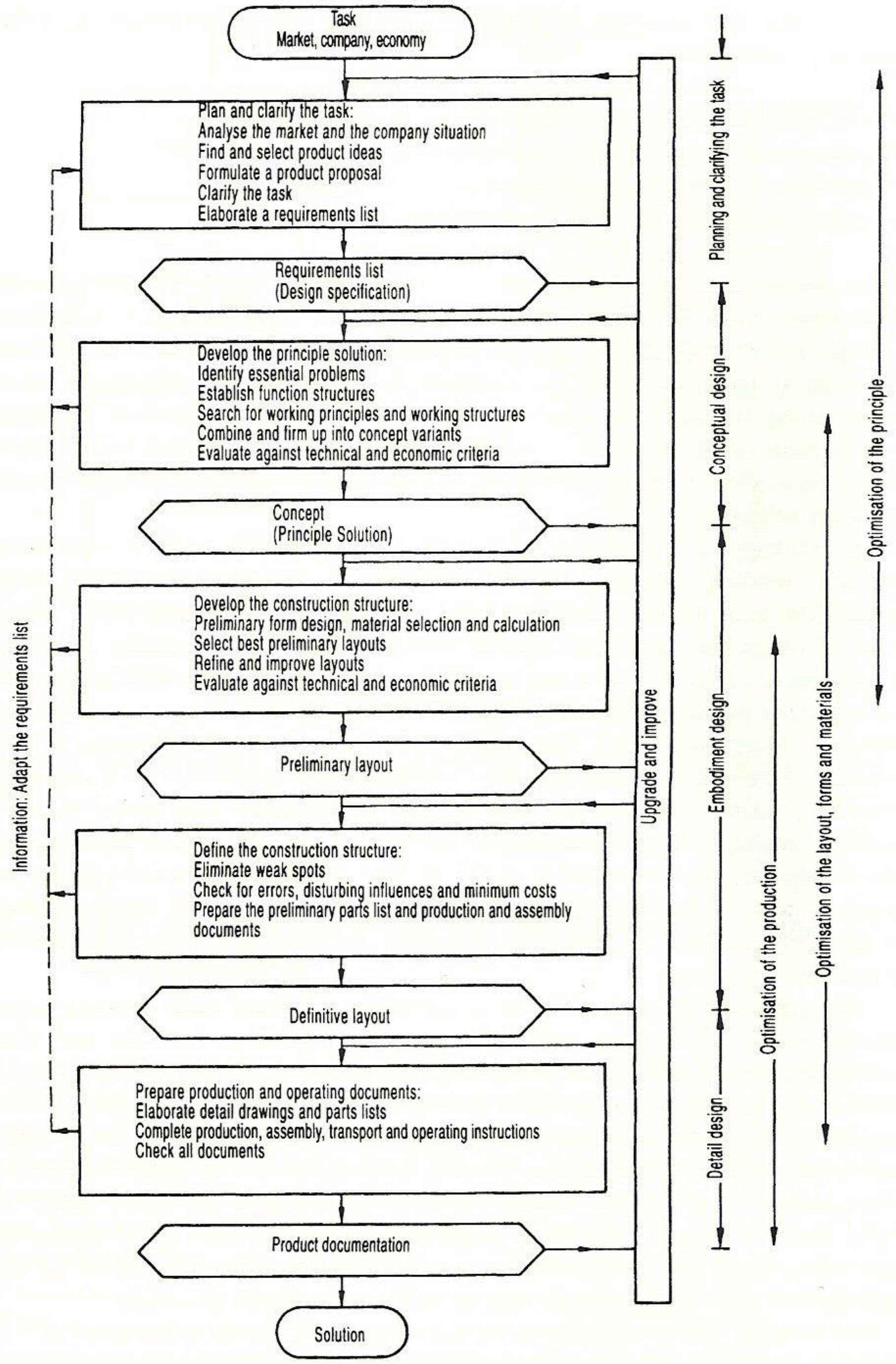

Figure 2.5 – Product Development Process – Classical literature
Source: Pahl and Beitz (1996).

In the first phase, Planning and Clarifying the Task, authors show how to elaborate product specifications. In it, maintainability is an item in a checklist with examples of maintenance applicability (e.g. change intervals, inspections, repairs, component replacements, painting and cleaning), serving as guidelines to be analysed in this phase. As any other requirement in the check-list, maintenance is not further explored, as the authors focus on demonstrating how a checklist is generated and leave details about other areas of interest behind. Nevertheless, through the explanation about the creation of the list and practical examples it is evident the need for generating clear requirements to be properly quantified (e.g. maintenance intervals for the component “x” must be for more than 12 months). Another relevant fact in the formatting of requirements is the outlining of items between “expectations” or “demands”, being the second critical and the first to-be-consider requirement.

On to the next phase, the Conceptual Design, the first step is to identify essential problems. A functional analysis is conducted and converted into functional principles, which, later on, are transformed into a functional structure. With the combination of these structures, different solutions are generated, which must pass through different “gates”, validating (or not) the concepts against the project’s technical and economic aspects. Again, maintainability is just remembered in a check-list and helps in the project’s validation during the conceptual phase. In this guide, simplicity, cleanness and easy inspection and repair access are mentioned, so that the possible chosen concept, at the end of this PDP phase, does not forget to contemplate maintenance aspects.

In the Embodiment Design, where the selected concept will undergo a metamorphosis, until it reaches the definite layout, another checklist is introduced with a set of basic rules for this stage. A key question is presented, aiming at identifying the possibility of executing/checking maintenance, inspection and reconditioning in a simple way. Right after this, Pahl and Beitz (1996) reinforce under “Clarity” and “Simplicity” that besides the items already-mentioned in the previous phases, other maintainability aspects must be observed, as follows:

a) Minimum use of tools, equipment and complex information during repairs;
b) Elaboration of a spreadsheet to set the product’s maintenance scope and schedule;
c) Certification feasibility for the recently carried-out repair, certifying it was (or not) duly performed;
d) Quick and easy identification of failures;
e) Simplified maintenance with low repair time.

Only by the end of the Embodiment Design the authors superficially discuss DFMT (Design for Maintainability). The following topics are examined:

a) Systems must be, preferably, free of adjustments and calibrations;

b) Limited number of parts in order to simplify the product;

c) Standard components to be selected whenever possible;

d) Allow free access;

e) Provide easy assembling/disassembling;

f) Apply modular modeling principles;

g) Reinforce, again, the use of the lowest number of tools possible.

In this section it is clear the influence of the product development engineer in the maintenance-cost composition and in its execution, as well as, choice of functional principles along the conceptual phase and throughout the preliminary phase.

Moreover, the authors state that the kind of maintenance, to be developed during the product's useful life, depends on the project's premises, such as availability, reliability, safety and the system's type (and respective specific functions). In other words, the maintenance will be corrective, preventive or predictive depending on the needs of the product's project (that is, the customers' needs). They also claim that during the Embodiment Design it is important to consider the accessibility and the assembly-centered project (DFA – Design for Assembly).

However, they consider that, ideally, a technical solution must be free of maintenance, by means of product with components of similar reliability. Pahl and Beitz (1996) understand that this decision is not technically feasible and it is even forbidden if the project's cost is taken into consideration. Thus, they list once again the different objectives within maintainability that are necessary to ensure the product's quick return to its original functionality.

Now, going to the Detailed Design, the authors are brief to describe this phase, only saying it is responsible for the layout details of the chosen technical solution. As far as maintainability is concerned, the importance of this phase in the development process is proven by the documentation of the product's operation and maintenance during its useful life.

Basically, from the moment the concept is set until a definite layout is reached, there is a "space struggle"[4] in the project. And it is exactly in these phases that the maintainability parameter has to be applied and carefully reviewed, from visual inspections with the help of virtual reality to physical inspections in actual prototypes. Although Pahl and Beitz (1996) insert maintenance in the description of all phases, showing short checklists and timely mentioning the maintainability parameter, they are not clear about how to work in PDP so that the necessary spaces, for maintenance and production, are assured. Furthermore, they do not give enough metrics on the subject and do not state how the maintenance requirements are to be monitored, from the Planning and Clarifying the Task until the Detailed Design.

For Blanchard and Fabrycky (2006), despite considering product's life cycle and maintainability during the entire development, in the virtual phase or in the test and validation phases, Maintainability-centered project proposed by the authors is basically focusing on metrics (e.g. MTTR). The authors are precise in mentioning different metrics to be followed or in proposing objectives related to maintainability. However, they are inattentive when trying to link such metrics to the development process along the Project so that the final product is developed to observe them. They finish picturing what must be achieved in terms of maintainability, but are not able to convert these objectives in clear PDP actions.

In common is the fact that they only mention CAD systems without clearly describing how designers could benefit from these powerful tools to incorporate aftermarket aspects (or even production issues) using virtual modelling of products in 3D models.

2.3 Design for maintainability

After reviewing the scope of maintenance, and how maintainability parameter is applied in the classical literature, it is important to comment on the guidelines given on design for maintainability.

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[4] Spaces in a 3D model are disputed, as there are different needs to be fulfilled. Many of these demands can even be conflicting. Therefore it is necessary to apply cost-benefit analysis' models.

2.3.1 Data collection

Field data collection is a key activity to understand how current products are performing in the market. As declared out in MIL-HDBK-470A (1997): "*Despite our best efforts to design properly and to validate the design through development testing, some problems may not evidence themselves until the product has been fielded".* Too long service standard times, low reliability in some components (quality problems), product misuse, manufacturing mistakes, too complex products, incorrect maintenance and/or expensive spare parts assortments are a list of possible issues found in the field that must be constantly addressed by the development team.

By compiling such data, new developments may count with a deep knowledge on problems to be improved. This data collection serve as a base to create a list of key-components that designers must carefully observe throughout PDP (directly connected to section 2.5.13).

2.3.2 Maintainability metrics

When looking backwards designers usually have field data collected. When looking forward for a new product to be developed with new technical challenges, it is vital to have proper requirements that assure the right product delivery in accordance with the company's objectives. They should compile both, improvements on earlier issues gathered from the market and a forecast of needs on future solutions.

Metrics can be separated into quantitative and qualitative measures. Quantitative metrics are figures that may be controlled by the development team such as Mean Time To Repair (MTTR). As for qualitative metrics, they are facts that are desired to be controlled such as: *No special tools are allowed to perform any service operation*.

Liu (2011) performed a literature survey and declared that quantitative conversion of qualitative requirements in maintainability engineering had not been conducted before his study. Some authors have tried to quantify some qualitative maintainability analysis based on deep field/service analysis.

2.3.3 Tools

Most products need tools during maintenance activities. The difference may be on the tools types, like universal tools (e.g. hand tools such as screwdrivers or a ratcheting wrench, see Figure 2.6), special tools (e.g. Figure 2.7), or even involving testability approach such as diagnostic computers.

Figure 2.6 – Virtual ratcheting wrench
Source: Moscheto (2009).

Figure 2.7 – Special tool made from universal tools
Source: Adapted from Moscheto (2009).

Normally, any project development should strive to minimize the need of tools as much as possible or at least keep the same tools' types as used from previous products versions. Special tools shall always be avoided, as they demand higher investments in the maintenance structure.

Tools are generally connected to fasteners. So in other words, the higher the number of different fasteners the higher the number of diverse tools will be necessary.

The assembling joints between components bring relevant information on how difficult or easy it is to remove such joints (COULIBALY; HOUSSIN; MUTEL, 2008). MIL-HDBK-470A (1997) brings some examples of standard removal/installation times on different fasteners types (Table 2.1 – refer to Annex A). Therefore, it is clear that the selection of a certain fastener may have a great impact on the maintenance standard time in the end.

Table 2.1 – Disassembling time for fasteners[5].

Description	Removal/installation (min)	Figure
Standard screws	0,42	AN.4
Hex or allen set screws	0,60	AN.5
Thumbscrews	0,14	AN.6
Machine screws (with nut)	0,67	AN.7
Nuts or bolts	0,78	AN.8
Retaining ring	0,27	AN.9
Drawhook latch	0,06	AN.10
Spring clip catch	0,07	AN.11
Butterfly latch	0,10	AN.12
Lift and turn latch	0,07	AN.13

Source: MIL-HDBK-470A (1997)

Besides ensuring a reduced number of tools and fasteners, associated with the consequent repair time, the DP team has to be able to analyse access needs, so the respective tools can reach the key-components. With CAD systems it is also possible to include a maintainability analysis to observe the existence (or not) of space to use universal (Figure 2.6) and special tools (Figure 2.7), using virtual models.

2.3.4 Standardization and simplification

Standardization aims the usage of common items. By this, meaning: fewer tools, less knowledge to repair, lower number of spare parts assortment; among others. Moscheto (2009) proposed a usage of a maintainability PTC plug-in (Figure 2.40) to support designers to improve the re-use of already available parts.

Bodein, Rose and Caillaud (2013) mentioned that on a German Automotive Manufacturer standardization there is a way to simplify products due to a uniform modelling and a uniform structure to start models.

Nevertheless, Dhillon (1999) warns about an excessive standardization exploration, to the point of rejecting new technologies, which would harm the natural advances in product development. Usage of common fasteners (like it is mentioned on

[5] All images refer to Annex A.

the earlier section), for instance, is a way to standardize a product without affecting its development advances.

Beyond standardization another approach in design for maintainability is to simplify product concept (e.g. Figure 2.8). Not only by using standard components, but also trying to reduce number of parts/assemblies.

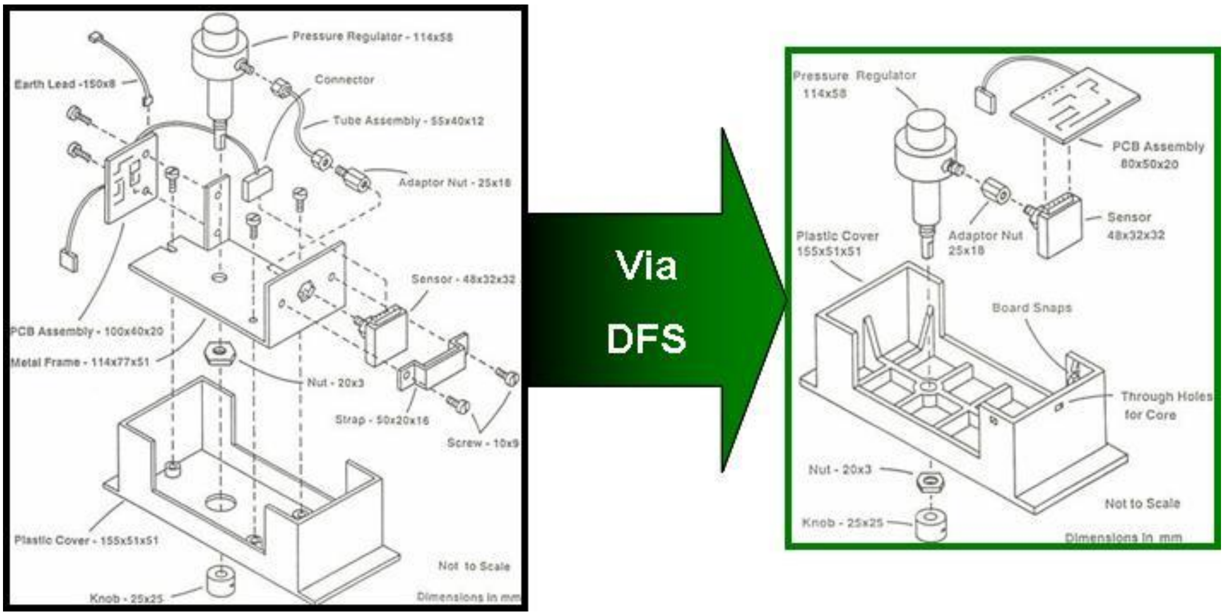


Figure 2.8 – Design For Serviceability - simplification
Source: Adapted from Huang (1996).

2.3.5 Modularity

According to Leon *et al.* (2012), modularity is to: "*design in separated parts, functional assembly units, thus, it is not necessary to dissemble the whole equipment in case of failure, but only the parts where the problem is located*".

"*The sub-assembly* (or module) *can be defined as parts collection which possesses complex assembly relationship and carry out same functions"* (WANG *et al.*, 2006). Figure 2.9 contains an example in which a design change facilitates a roller bearing repair as on the new modelling its lower case has been divided to enhance component access.

Then, by applying a modular design it guarantees independence and interchangeability between units in fulfilling all products' functions (WAHAB *et al.*, 2008).

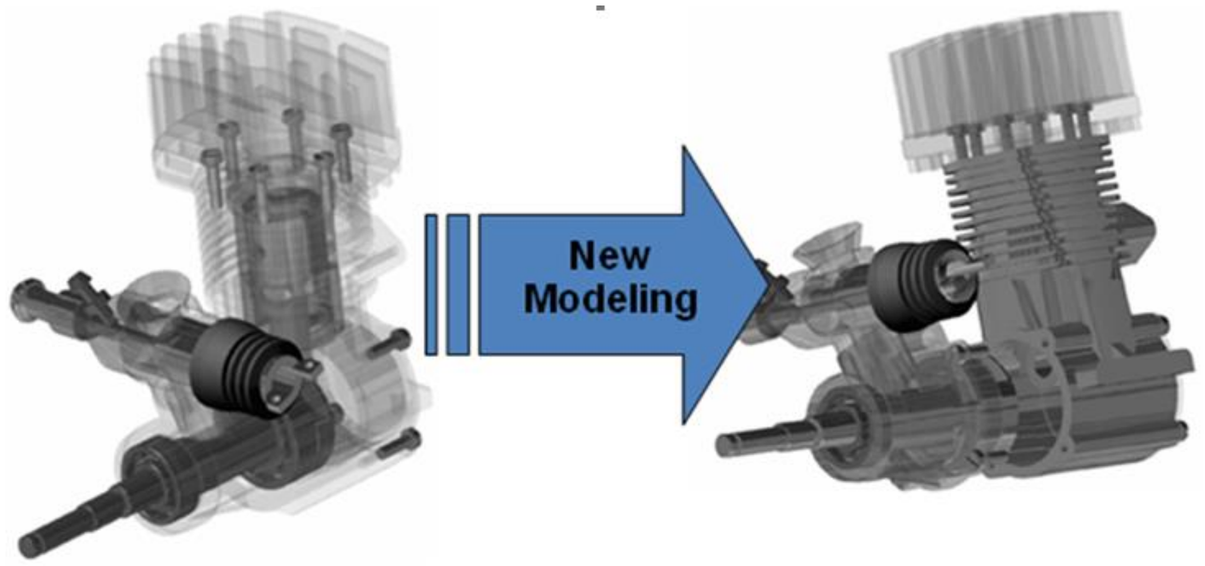


Figure 2.9 – New modeling considering Modularity
Source: Adapted from Moscheto (2009).

2.3.6 Ergonomics

The definition of Ergonomics for Leon *et al.* (2012) are the *“space requirements in order to set-up the proper working conditions for the development of maintenance activities. This attribute also assesses requirements in locations and spaces where materials to manipulate can be placed when it is necessary to perform interventions on the physical system*”.

Zhou *et al.* (2014) considered maintenance space as an important maintainability aspect influencing directly the operator’s comfort and performance. They have proposed a method using swept volumes of maintainer’s hand and tool to evaluate maintenance space (similar somehow to what JUNIOR, 2015 developed). Zhou *et al.* (2017) adds to this definition that the lack of workspace for maintenance activities leads to extra time to perform such maintenance tasks.

Some examples of spaces needed in order to perform maintenance actions are expressed on Annex A. They represent some human interaction with tools, inspection windows, and complete necessary spaces for maintenance activities. On Annex A, **Figure AN.1**, **Figure AN.2** and **Figure AN.3** bring very important information about space needed in order to be able to remove fasteners with standard tools. These figures will be further explored along the research, as they will be very connected to this thesis' investigation.

Another important ergonomic input is the hand size. Junior (2015) used a P95[6] male hand as a reference in his plug-in proposal (swept volumes simulating fastener removals). Basically, a P95 male hand (Figure 2.10) has the following sizes: a = 197 mm, b = 112 mm, c = 89 mm, d = 217 mm (hand perimeter) and e = 30 mm. These ergonomic inputs will be further explored in this research.

Note: Woodson (1981) presents slightly different sizes for a P95 male hand: a = 203 mm, c = 97 mm and e = 33 mm. Nevertheless, Junior (2015) reference will be used along the research.

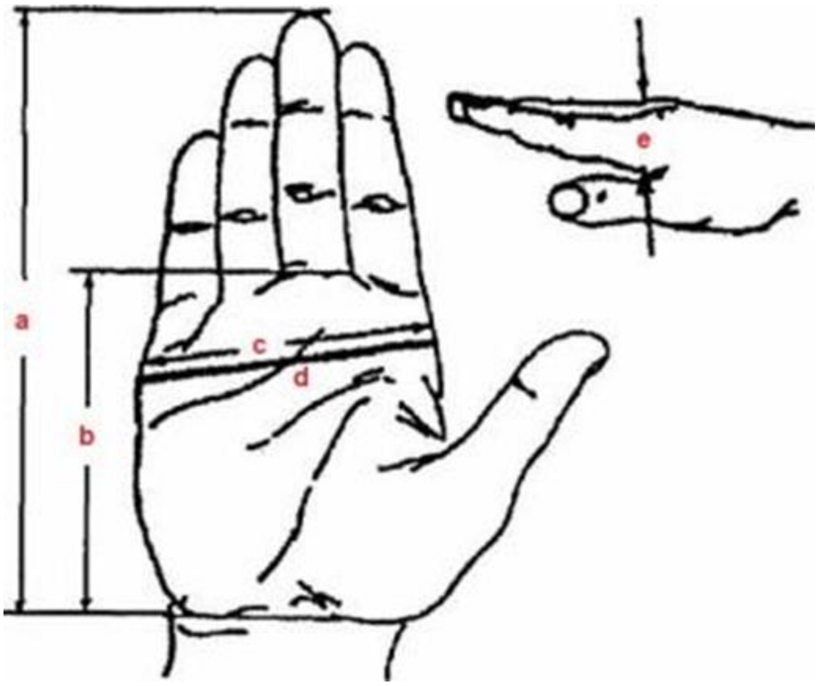


Figure 2.10 – Hand sizes – ergonomic metrics
Source: Adapted from Zhou *et al.* (2014).

Moreover, nowadays there are specific virtual software capable to perform ergonomic evaluations (e.g. DELMIA and IMMA – see section 2.5.12). The analysis normally focuses on visibility, strength and accessibility. Further information is given on this regard on section 2.5.

[6] P95 (95th percentile value) represents that 95% of the population has smaller hand sizes if compared to the above dimensions (WOODSON, 1981).

2.3.7 Accessibility

On preventive and corrective maintenance procedures, it is vital to have easy access to components and/or complete modules that are usually replaced or maintained. Beyond that, it is of fundamental importance to have free inspection visibility and full access to any fasteners holding the key component to be replaced.

Another important point to highlight to designers is to avoid as much as possible removal of any other modules prior to reach the desired component (MIL-HDBK-470A, 1997). For example, in order to replace an air compressor in a commercial vehicle it is no good to have to remove fuel lines. From a reliability point of view, besides increasing the service standard time, two sub-systems will have to be considered/checked when re-installing the air compressor (fuel and air compressed systems).

Accessibility may be verified using CAD systems and virtual reality. Next section discusses this matter. To reinforce the literature review on maintainability, Appendix A shows a set of directives, from different authors (compiled by MOSCHETO, 2009). Another option for literature review is to use Sulevis (2015) maintainability basic rules.

2.4 CAD systems and virtual reality

According to Bodein, Rose and Caillaud (2013), to be efficient when using CAD systems the following items shall be considered:

a) Reduce design time in all PDP phases (conceptual, preliminary or detailed);

b) Reduce CAD models and geometry;

c) Accelerate the automation of routine design tasks based on Knowledge-based engineering (KBE) applications;

d) Enhance simultaneous engineering;

e) Improve CAD models quality.

As maintainability improvements usually require important changes in the product layout, it is the outmost importance to anticipate maintainability evaluations as precisely and accurately as possible in PDP (BARABADI; BARABADY; MARKESET, 2011), by using virtual reality and CAD systems as soon as virtual products are mature enough to start maintainability analysis (at least on Definitive Design, see Figure 2.11).

MIL-HDBK-470A (1997) states that maintainability is really a parameter to be considered in the design as any attempt to improve maintainability, after the “freezing” of the product development, will be expensive and inefficient.

Jie (2011) believes that the lack of computer aided analysis tools, which are easy to master and use, is an important factor which impacts in the absence of maintainability analysis. Gaoling *et al.* (2010) confirms that maintainability analysis are lacking. They refer to this analysis as being invisible and not vivid, still depending heavily on physical mock-ups.

Kim, Kim and Choi (2011) have proposed a knowledge space to enable different departments to share their ideas, information and knowledge in order to perform better real-time decisions. The collaboration supports quick answers to customer demands, as it reduces development time/costs due to faster fixing conflicting issues.

Simultaneous engineering through virtual activities is an approach that enables product engineers to better understand different demands from other functions in the company. It results in a product more adjustable to the present industrial facilities and/or existing equipment/knowledge to accomplish product’s field maintenance. Virtual reality allows checking the maintainability parameter even before an actual model or prototype is produced (HAO; YU; XUE, 2002).

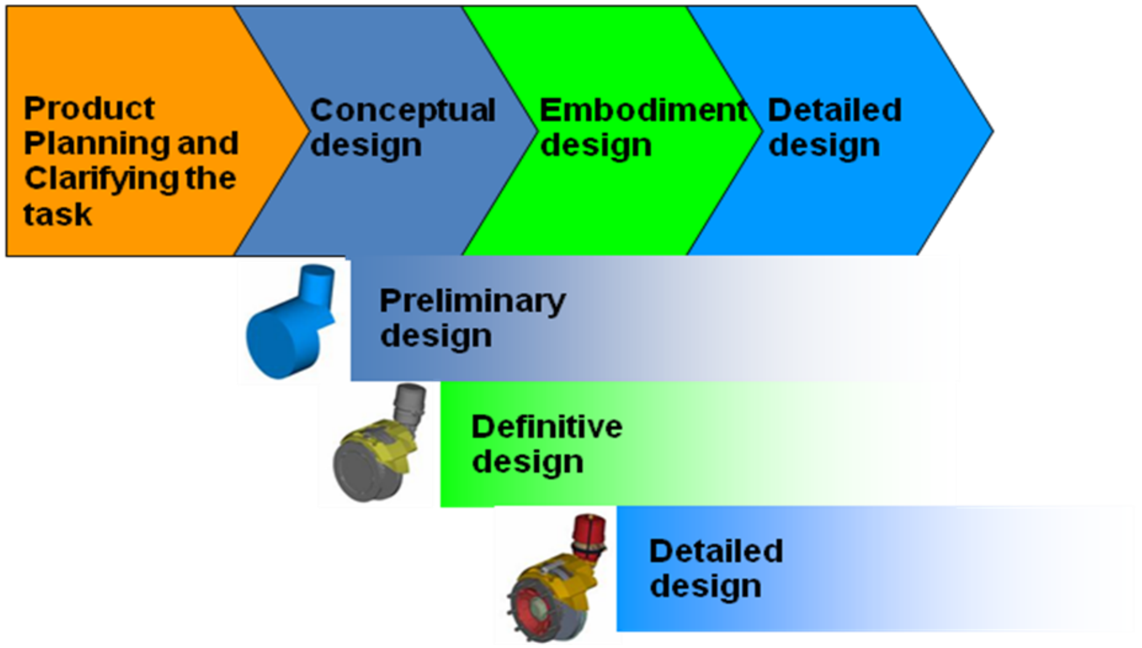


Figure 2.11 – PDP modeling evolution
Source: Moscheto (2009).

Normally, common ways to support simultaneous engineering are the design reviews meetings. They are attended by multidepartment staff, where virtual prototypes are used with 3D product models for such multidisciplinary discussions. All stakeholders try to accomplish their own needs in design reviews (manufacturing, aftermarket, commercial areas, among others) which implies a tough discussion and a space struggle to attend all requirements coming from company's different sectors.

From a maintainability point of view, service engineer will use virtual environment to analyse the following topics (MIL-HDBK-470A, 1997):

a) Reachability and access;

b) Field view;

c) Ergonomics (e.g. section 2.5.12);

d) Checking of maintainability directives;

e) Checking of standard times;

f) Checking of repair sequences;

g) Checking product standardization and simplification;

h) Modularity;

i) Use of existing special and universal tools;

j) Cost-benefit analysis (together with other project's functions).

Generally, maintainability analysis relies heavily on service engineer field experience. Therefore, the potential knowledge gap that can exist from the product designer up to the service engineer creates a need of several virtual reworks on 3D models when a design review occurs.

Recovering the findings on classical literature, on today's CAD systems there are few tools that have a direct support for maintainability analysis helping the designer to fulfil a maintenance requirement (such as MTTR) and understand the actions needed to accomplish to it.

Some virtual tools usage proposals are reviewed on the following section aiming at maintainability analysis. Their gaps and some future enhancements for the current thesis proposal are then highlighted.

2.5 Maintainability tools

The majority of existing maintainability tools to analyse product maintenance is normally based on expert's knowledge of similar product maintenance and past data (JIE, 2011).

2.5.1 Fuzzy logic to assess maintainability

For Yang, Xia and Yang (2009) it is difficult to describe a relationship between maintainability and parameters by a mathematic function. Instead, they have used a method linking fuzzy theory and neural network.

Lu and Sun (2009) use a civil aircraft virtual mock-up as case study to evaluate maintainability aspects according to a checklist. DELMIA system (*Dassault Systemes* Virtual Manufacturing Platform) was the CAD system applied during this study. Evaluation model was based on Fuzzy Multiple Attribute Decision-making. Items judged were: visual accessibility, reachability accessibility, disassembly accessibility, simplicity, modularization, standardization, testability, ergonomics and identification. This approach is highly dependable on maintenance experts, as a lot of experience is needed to be able to quantify or qualify the different maintainability design attributes.

Yu, Peng and Liu (2011) have used virtual environment with VR gloves and helmet to simulate wheel maintenance (very simple with full access to fixing elements example). Users simulating the maintenance operation give scores from "Very bad" to "Very good" in different factors (design, structure, supportability and human factors – see example on Figure 2.12). Authors have connected the evaluations with a Fuzzy Matrix in order to conclude how good or bad is a solution from maintenance point of view.

Slavilla, Decreuse e Ferney (2005), proposed a tool in which the development team is actually weighting the maintainability factors (standardization, modularity and easy of assembly) using linguistics terms in order to evaluate a solution (Low, Medium or High for each evaluated factor). In the end, the tool grades the product solution from 0 to 1 (one being the best maintainability scenario).

All of these fuzzy tools deeply rely on the development team experience, and works more on a Design Review approach when the CAD solution is already in place. No support is given though to enhance designers thinking on maintainability when virtual products are being in fact created/designed.

Table II Evaluation scores of design factors

	Evaluation score				
Second layer index	Very good	Good	Common	Bad	Very bad
Simplicity	0.55	0.25	0.20	0	0
Accessibility	0.50	0.20	0.20	0.10	0
Standardization/ modularization/ reciprocation	0.55	0.20	0.15	0.10	0
Measurability	0.50	0.20	0.15	0.10	0.05

Table III Evaluation scores of structure factors

	Evaluation score				
Second layer index	Very good	Good	Common	Bad	Very bad
Frame form	0.60	0.15	0.15	0.05	0.05
Base form	0.55	0.20	0.15	0.10	0
Door or cover form	0.50	0.30	0.20	0	0
Disassembly unit	0.55	0.15	0.10	0.10	0.10

Figure 2.12 – Evaluation scores for fuzzy analysis
Source: Yu, Peng and Liu (2011).

2.5.2 Maintainability index for mechanical components

Similarly to the authors of the fuzzy logic tool, Wani and Gandhi (1999) tried to create metrics for the maintainability assessment of mechanical components. The authors proposed different maintenance requirements (e.g. accessibility, standardization, tooling need, among others), which are interconnected, with different interaction levels (strong, medium, weak and no connection at all). Different attributes are evaluated based on experience designers in the relevant modelling. All these assessments are then summarized in matrices that will be narrowed down to a proposed product maintainability index. The tool proposed does not support the development engineer at all in CAD environment / mathematical interactions.

Even though Coulibaly, Houssin and Mutel (2008) have gone deeper in their study by using CAD systems to collect some information on components within a modelling proposal, their tool is also very hard to be applied in practice as the development team needs to define the repair sequence manually.

Abdullah *et al.* (2006) have used a case study of a power window of a passenger car, structuring the analysis of a motor replacement. They also proposed to create a disassembly graphs and define the assembly criteria in order to calculate maintainability index. Both approaches are not feasible in practice, because they have to be created manually.

Mason (1990) suggested the usage of The Bretby Maintainability Index (Figure 2.13). First, it is necessary to define all involved tasks to perform the machine maintenance and their frequencies. Then, every task needs to be described in a detailed level in order to match it with the Bretby Index. In the end, a score is computed also taking into account some ergonomic factors. At that time, 1990, author had suggested to perform such evaluations on physical prototypes or using arrangement drawings. Nowadays, by analogy, the same index could also be applied by using virtual realities instead.

The Bretby Maintainability Index

Factors	Points score
Access	
PART 1. HATCHES AND COVERS	
(a) Flip-up cover or flap – no fasteners	3 per cover
(b) Door or cover (hand operated fasteners)	4 per cover
(c) Door or cover – single fastener (tool operated)	5 per cover
(d) Door or cover – multiple fasteners (tool operated)	10 per cover
(e) Lift off/lift up panel – easy to handle, < 12 kg	2 per cover
– 12 to 24 kg	4 per cover
– 25 to 35 kg	6 per cover
– > 35 kg	10 per cover
PART 2. APERTURES	
KEY	
H = height off floor (mm); *d* = depth inside aperture (mm)	
h = height of aperture (mm); *w* = width of aperture (mm)	
For all tasks	Score for each fastener/component
(a) Obstructed access to/around component – moderate	2

Figure 2.13 – The Bretby Maintainability Index
Source: Mason (1990).

2.5.3 WP method (Wave Propagation)

Wave propagation method was proposed by Srinivasan e Gadh (1998 e 1999) e Gadh et al. (1998) contributing on the disassembly sequence planning through a geometric algorithm. Their ambition is determine the most optimized disassembly sequence of a target component in a complete product.

Authors claimed that WP may be used for applications such as maintenance, reuse and recycling. On the maintainability side they also proposed metrics to compare different CAD models on this regard:

a) Number of parts to be removed;

b) Accessbility;

c) Componets volumes;

d) Material type.

In order to use this geometric algorithm there are three assumptions highlighted by Srinivasan and Gadh (1998):

a) "*The relative motions of the components are determined without considering the tools, fixtures or robots required to achieve these motions".* This, of course, limits a lot the usage of WP when trying to investigate if a CAD solution being proposed is good or not for the aftermarket;

b) "*Assemblies are assumed to be polyhedral, rigid (no deformable), frictionless and defined by nominal geometry (no tolerances) with tightly fitted components".* Again, the fact that tolerances are forgotten, reduces the applicability of this algorithm, as in maintenance actions tolerances have a great impact on the service actions (e.g. removal of a roller bearing from its case);

c) "*Components are disassemble. Moreover, local disassembly of components are considered for disassembly sequencing".*

Chung and Peng (2005) tried to move one step further to support CAD specialist. They criticized the fact that WP did not handled tools access and neither disassembly of complete modules (sub-assemblies) in order to shorten the access path for a wanted component. On the other hand though, the case study proposed by the authors did not give a proper disassembly sequence based on a tool access which minimized the advantages of their study.

Moscheto (2009) use WP method to create a Positioning Indicator tool for Aftermarket Key-components (see Figure 2.14). The main focus of this indicator is to help CAD specialist to understand, even prior of Design Review, how good or bad allocated a key-component is (aiming at a lower rework load on designers). This tool was created as a Plug-in in ProE/PTC and basically calculates the number of parts to be removed in order to reach the target component in relation to the product total number of parts available. Low number of parts to be removed is a positive solution (green colour). If on the opposite way, there are a great number of parts to be extracted, parts will be highlighted in red. Failure frequencies are also included in the analysis serving as a weight factor. Some caveats on this solution:

a. Number of parts to be removed can be wrong as WP does not consider space between parts or relative movement among parts;
b. Modularity cannot be properly identified by the plug-in which leads to misjudgements;
c. Lack of tolerances also misleads the tool, as some impossible service actions are considered to be plausible solutions;
d. On complex products there is a doubt if total number of parts from this indicator should be allocated on a module or in the complete product.

Therefore, to proper use tool in practice, there are a number of weaknesses that needs to be correctly addressed (just like the assumptions mentioned earlier from WP method usage).

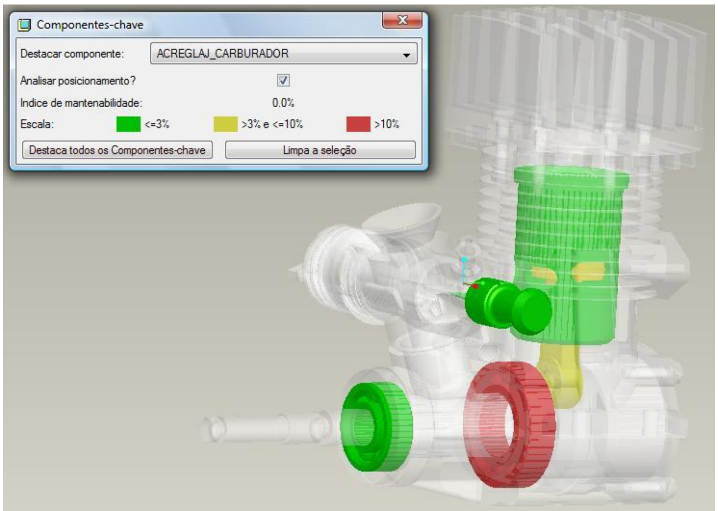


Figure 2.14 – Positioning analysis of key components
Source: Moscheto (2009).

2.5.4 Metaheuristic method

Zhong *et al.* (2011) produced an interesting review of several different disassembly methods in which the majority are focusing on Project for Assembly/Disassembly - concept developed by Boothroyd, Dewhurst and Knight (1988). These studies have utilized metaheuristic algorithms such as Petri nets, genetic algorithm, graph theory and mathematic programming methods aiming on complete disassembly or tear down (Recycle Design).

For maintainability, these authors correctly conclude that, the objective is only to replace the target component (failed part or preventive component to be replaced). Therefore, the disassembly list should only focus on the parts that are interconnected with each component.

To improve the disassembly methods Zhong *et al.* (2011) have proposed to use Dijkstra algorithm (without fixing elements) and Particle Swarm Optimization (with fixing elements) in order to improve disassembly sequences. Authors have made a comparison table showing advantages and disadvantages of different methods (Figure 2.15).

Methods	Applicable field	Advantage	Disadvantage
Dijkstra's algorithm	Optimization problem like status space searching	The procedure is simple and easy to understand, performance is good when component number is less	Performance is very bad when component number is large
Wave propagation	Optimization problem like status space searching	Performance is better than Dijkstra's algorithm when component number is large	The procedure and method is complicated
PSO	All optimization problem	Simple to understand	Sometimes it cannot get optimum value
Genetic algorithm	All optimization problem	Good optimization capability	A little complex than PSO
Ant colony optimization	All optimization problem	Good optimization capability	A little difficult to understand

Figure 2.15 – Comparison of different methods
Source: Zhong et al. (2011).

The drawback from the study is the fact that components' interference tables (base for algorithms calculations) is not fully explained how the conversion from CAD system to these tables occurs.

2.5.5 Hybrid graph disassembly model

Wang et al. (2006) proposed a Hybrid Graph model in order to support a sequence planning aiming on product maintenance. The hybrid model expresses the level of constraints among the different components within the selected product. It is a manual procedure very hard to be practicable in real life developments mainly on complex products. In order to define a maintenance sequence, authors have considered the importance of evaluating sub-assemblies to reduce the number of parts to be removed for reaching the selected component to be maintained (Figure 2.16).

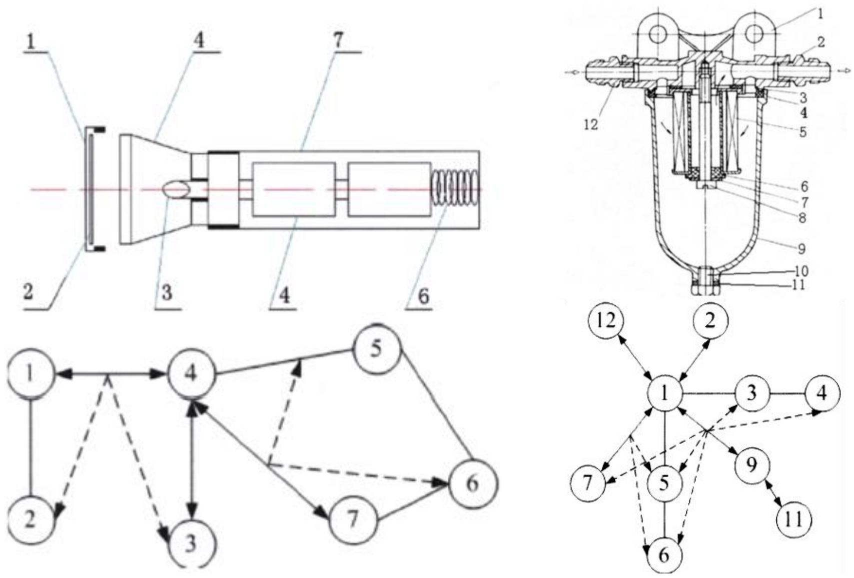


Figure 2.16 – Flashlight and fuel filter hybrid graph models
Source: Adapted from Wang *et al.* (2006).

2.5.6 Virtual maintenance analysis

Virtual reality is useful to reproduce a virtual representation of product parts and can be used as a collaboration tool (ANASTASSOVA; BURKHARDT, 2009). There are two ways to consider virtual reality when performing maintenance analysis: i/ non-immersive; and ii/ immersive.

By the non-immersive 3D systems are used as a base to simulate a working environment and therefore a virtual analysis (e.g. Delmia).

An immersive virtual reality is connected to the usage of headsets which allows the user to perceive a virtual environment (simulating a given scenario) with its physical spaces. The concept of VR is to simulate the user existence in a virtual atmosphere. Normally in a VR system users also experience different audios and/or vibrations either via extra sensors (e.g. data glove from Figure 2.25) or via joysticks as a feedback to the user virtual movements (haptic systems).

2.5.7 Non-immersive virtual maintenance analysis

Geng *et al.* (2013) created a model to evaluate maintenance safety in a virtual environment (basically using DELMIA). Their method is divided into four different criteria (Figure 2.17). Every criterion is evaluated from rank A to C (according to Figure 2.18). Due to relevance in this specific study, only the following criteria will be described:

a) Accessibility design:

  a.1) Visibility design: technician should have a clear view of the component to be maintained (see Figure 2.34 and Figure 2.35 - DELMIA);

  a.2) Reachability design: component to be repaired and/or replaced should be reachable (see Figure 2.36 - DELMIA);

  a.3) Operation space design: needed space to perform service operation is available;

b) Ergonomic design:

  b.1) Focus on man-machine interface (physiological and psychological aspects).

Authors have analysed snapshots from DELMIA (example on Figure 2.19) to perform the evaluation method using an Analytical Hierarchical Process (AHP). Either to define the weight factors in the AHP and/or to perform the actual snapshots evaluations a great level of experience is needed on both, virtual environment tool and on maintenance procedures.

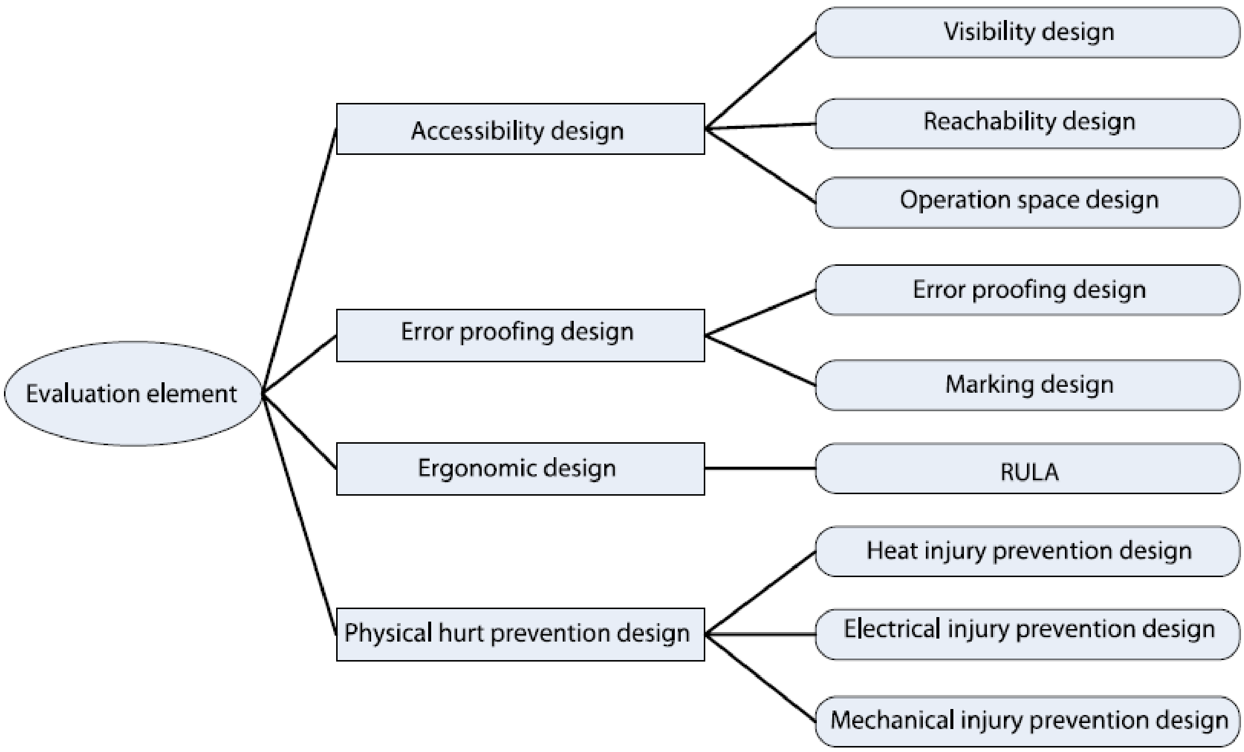


Figure 2.17 – Different evaluation criteria
Source: Geng *et al*. (2013).

Evaluation element		Rank A		Rank B		Rank C	
		Criteria illustration	Corresponding embodiment in VME	Criteria illustration	Corresponding embodiment in VME	Criteria illustration	Corresponding embodiment in VME
Accessibility design	Visibility design	Target could be seen directly	Target locates in the best vision area	Target could be seen partly because of interruption	Target locates in the widest vision area after adjusting	Target could not be seen at all	Target locates in the invisible vision area after adjusting
	Reachability design	Maintenance could reach the target easily	Target locates in the envelope	Maintenance could not reach the target	Target locates out of the envelope	Maintenance personnel may try to approach instinctively	Target locates just around the boundary of envelope
	Operation space design	Maintenance personnel could operate freely	Collision warning occurs hardly	Maintenance personnel collides with surroundings sometimes	Collision warning occurs sometimes	Maintenance personnel always collides with surroundings	Collision warning always occurs
Ergonomic design	RULA	Acceptable ergonomic design	Final score is 1 or 2 with green color	Ergonomic design need to be investigated further and change soon	Final score is 3–6 with yellow or brown	Ergonomic design need to be investigated further and change immediately	Final score is 7 or higher with red color

Figure 2.18 – Evaluation Criteria's ranks
Source: Geng *et al*. (2013).

Chen and Cai (2003) propose a vector projection evaluation method over 13 different Maintainability evaluation factors. They also use AHP to weight factors under analysis. In the same way as Geng *et al.* (2013), authors suggested the usage of pictures from two different systems in order to perform a design review.

Zhou *et al.* (2014) have devised the usage of swept volume from the maintainers' hand and maintenance simulations using DELMIA (taking the time that it takes to perform a virtual action) in order to evaluate a maintenance operation in a quantitative manner. The objective is to evaluate if there is sufficient maintenance space reserved or not. Authors consider in their maintenance analysis the approaching, unscrewing and leaving movements (Figure 2.20).

In summary, Zhou *et al.* (2014) have used swept volumes to verify maintenance space in virtual environment (Figure 2.21) and Geng *et al*. (2013) have gathered 3D snapshots in order to perform maintenance evaluations. In common, both studies have used DELMIA and created evaluation criteria tables to support their maintainability analysis. All these works, at the end, are proposing different ways to simulate and evaluate maintenance activities.

The drawback in these proposals though is the fact that such analysis are performed in one moment in time, and it is not possible to use them to guarantee needed maintenance space along the complete product development cycle (like it is envisaged by by using space claim concept).

Pan, Wang and Du (2014) have focused on the assembly procedures using path planning techniques. Firstly they build a disassembly matrix based on CAD models data. By using collision detection they mapped the disassembly steps needed to dismount a complete product (Figure 2.22). Then, in the end, the assembly paths are formed on the inverse order of the disassembly process. For maintainability purposes, their ideas of disassembly based on continuous collision detection method could be quite useful on virtual analysis.

2.5.8 Immersive virtual maintenance analysis

Qiu *et al.* (2014), Dong, Le and Chuan (2013), Li *et al.* (2012), Wu *et al.* (2011) and Yu, Peng and Liu (2011) have used VR technologies with gloves, helmets and tracking tools to simulate maintenance operations.

Figure 2.19 – Reachability analysis
Source: Geng *et al*. (2013).

a) Approaching operation b) Unscrewing c) Leaving operation

Figure 2.20 – Swept volume to verify maintenance space
Source: Zhou *et al.* (2014).

Figure 2.21 – Swept volume to verify maintenance space – Hand volume
Source: Zhou *et al.* (2014).

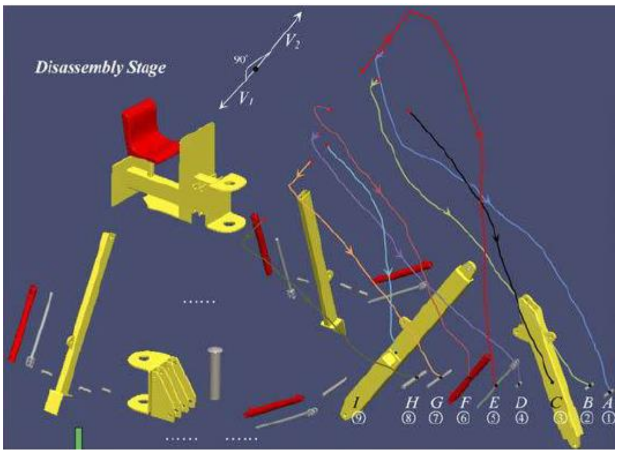


Figure 2.22 – Disassembly stage
Source: Pan, Wang and Du (2014).

Qiu *et al*. (2014) have used data glove, helmet and tracking tools to simulate a hydraulic motor replacement. Authors propose the usage of software developed by their lab to simulate and to automate the analysis of human factors (visibility, operation comfort and reachability). Based on maintenance scenes stored in a database, the automatic analyses are created on pre-defined rules/scores. Figure 2.23 brings an example of visibility analysis. In the end, a comparison is made between their own developed software versus Delmia. According to their conclusion their system is more automated than the work load that users had to go through with Delmia analysis.

Qiu *et al*. (2014) brought new light to maintainability study as it proposes to automate the maintenance scene analysis. However, engineers that took part on the research had to fully understand all maintenance steps prior to service operations simulation (this is actually stated in the research). The drawback is that the experience of the task was already in place when operators would simulate the method operation. Nevertheless, some ideas on the results automations could be used further on maintenance scene analysis.

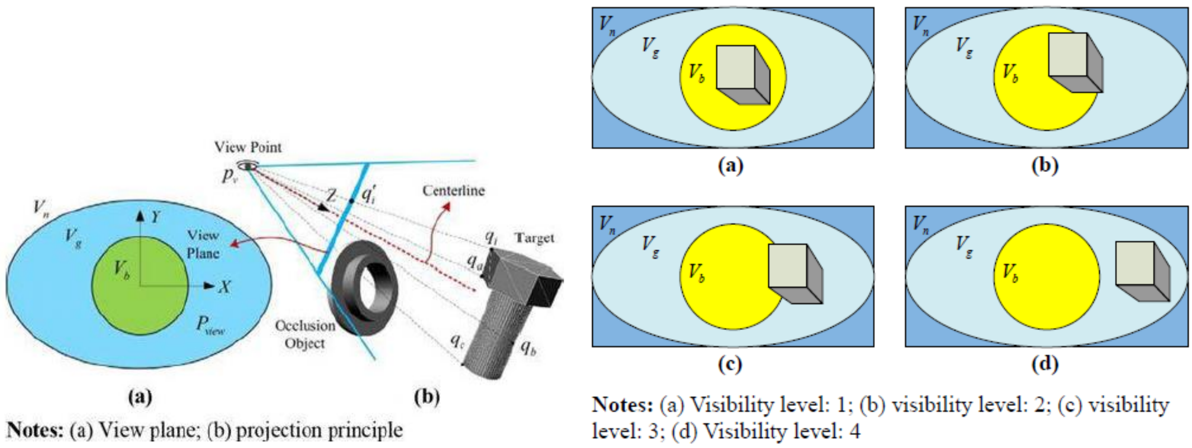


Figure 2.23 – Visibility level analysis
Source: Adapted from Qiu *et al.* (2014).

Dong, Le and Chuan (2013) focused on maintainability verification and maintenance time prediction on virtual environment. There is a clear statement on the research saying that the person who performs the virtual verification has to communicate with developers and skilled technicians to collect all needed details to fully comprehend routes, postures, tools and procedures to be applied in the analysis. In other words, their method relies mostly on experience when performing the maintenance evaluation. Authors propose some formulas to calculate time spent when performing a simulation. Visibility, reachable and disassembly accessibility, and finally working posture are factors evaluated qualitatively to support the calculation. DELMIA (Non-immersive), an Immersive simulation (using helmet, tracking tool, among others) and the actual maintenance time are used to compare with proposed calculation to prove that their methodology based on manikin's movements (therblig-oriented decomposition of maintenance tasks) is useful.

Li *et al.* (2012) have proposed a collaborative maintenance training on complex products based on an immersive virtual reality. Authors have been able to use multi operators to conduct a case study of replacing the sealing ring of a multilevel hydraulic cylinder (Figure 2.24). However, apart from simulating a service operation, they realize the importance of moving one extra step, to integrate in their system maintainability verification and human factors evaluations.

Qiu, Fan and Wu (2013) reinforce the importance of operators simulation on virtual maintenance and virtual assembly on mainly two scenarios: i/ if there is enough space for different people sizes (with tools included) to perform their tasks; and ii/ to predict/judge task's comfort, controls access, visibility and forces to be applied (ergonomically speaking) to guarantee the right safety environment level.

They criticise DELMIA / JACK (commercial virtual human software based on forward kinematics and inverse kinematics algorithm to define human motions) as being very hard to be used, as only skilled engineers with deep understanding of biomechanics are able to make the motions truly connected to reality. Authors have used a virtual human (VH) driven in real-time by an operator (Figure 2.25) in DMSP (Digital Mock-up Simulation Platform – developed by Computer Integrated Manufacturing Institute, Shanghai Jiaotong University).

A case study is presented by which several graduation students with previous VR expertise/training had to assembly connecting rods caps in an engine (Figure 2.26). They were asked whether it was better to simulate the assembly with a complete virtual human or just a virtual hand. Result may be seen on Figure 2.27.

Qiu, Fan and Wu (2013) study has been able to propose a new tool to simulate assembly and maintenance tasks in an immersive manner. However, even though results seem to be quite impressive, from the thesis proposal author's view is still evaluating a design that has already been deployed. Therefore, there is still room for proposing tools enhancements in which designers could benefit to create products to be better assembled or maintained with guided tips or simulations reducing rework costs / simulation analysis.

Lawson, Salanitri and Waterfield (2016) proposed some future directions to further develop virtual reality based on interviews with company staff of one automotive company. Some interesting points emerged on their research about the usage of immersive analysis such as: i) users with issues regarding depth perception mostly on short distances; ii) access to the VR technology once not all sites from this specific company have VR installations; iii) lack of force/torque feedback and/or any other haptic feedback (reach, clash/collision, sound and vibration) which the authors consider an important feature to use on design and ergonomic evaluations; among others.

Figure 2.24 – Collaborative virtual training.
Source: Adapted from Li *et al*. (2012).

2.5.9 Non-immersive versus immersive virtual maintenance

Li *et al.* (2009) have produced a comparison between immersive and non-immersive virtual maintenance analysis.

According to the authors non-immersive advantages are:

a) Complex maintenance environment (with several workers and large scenes) it is easier to adopt non-immersive tools;

b) Simulate movements that are not possible to be performed on immersive tools (e.g. climbing a ladder).

Imersive systems advantages:

a) Operation failures are diminished as the immersive tools create a more real maintenance environment;

b) The interaction of immersive tools (gloves and helmet giving feedback of interferences for instance) helps building up more truthful results.

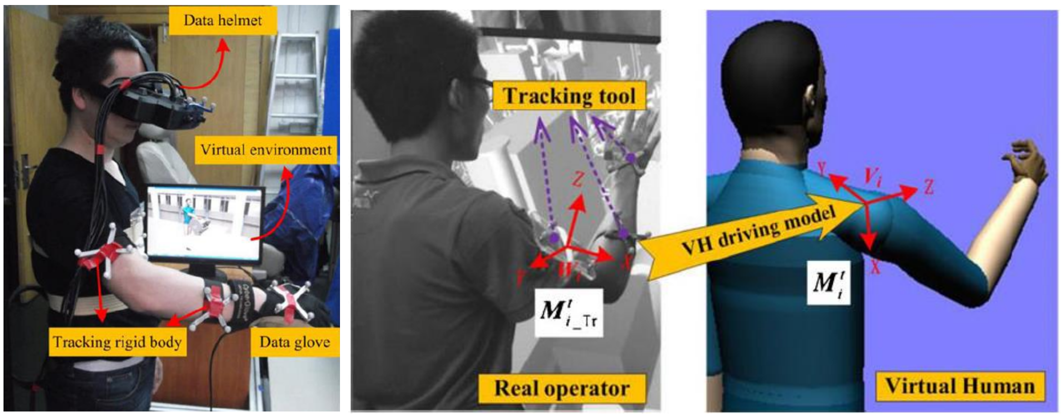


Figure 2.25 – Virtual human driven in real time on DMSP.
Source: Adapted from Qiu, Fan and Wu (2013).

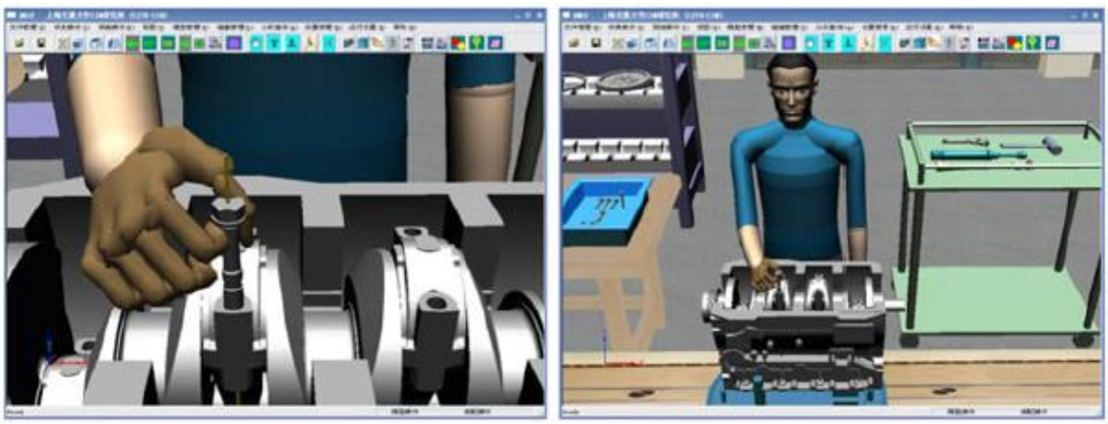


Figure 2.26 – Case study – connecting rod assembly.
Source: Adapted from Qiu, Fan and Wu (2013).

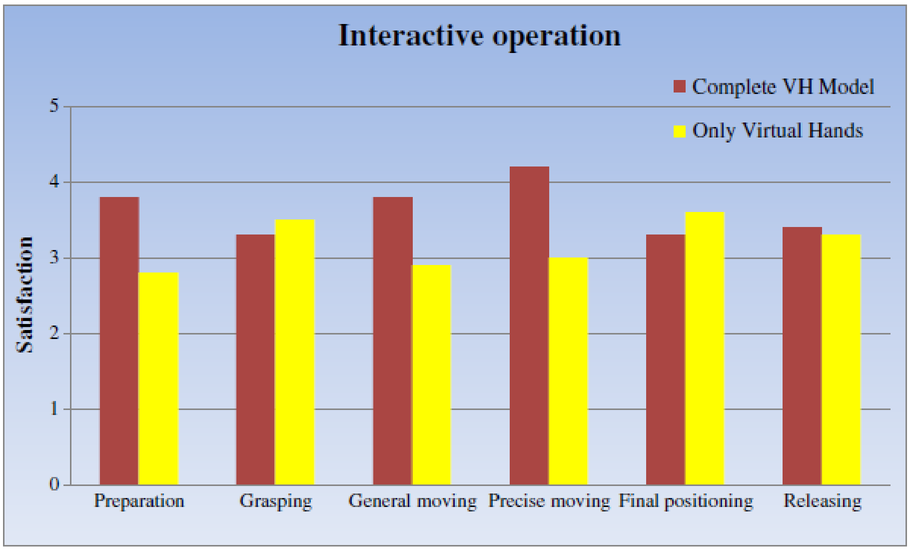


Figure 2.27 – Case study – survey result.
Source: Adapted from Qiu, Fan and Wu (2013).

When it comes to maintainability analyses Li *et al.* (2009) mentioned that on non-immersive systems, it is possible to evaluate interferences/collisions, view reachability, static comfort degree and operational space of tools during the maintenance task simulation.

On the other hand, they claim that on immersive environments maintainability evaluations are more intuitive and accurate. The authors mentioned that complex problems are solved in an easier way on immersive systems as real feedback given by data gloves / helmets making the analysis more accurate on access and maintenance spaces. Ergonomic analysis is intuitive as the person simulating the actions is indeed repeating the same gesture on real life. In their conclusion, they realize that for some analysis a mix between non-immersive and immersive systems might be needed to extract full potential from the systems.

However, on this study one important topic that was not considered with the necessary prioritization is the actual background experience necessary to simulate maintenance operations on both environments (immersive and non-immersive). Can the result of a maintenance analysis performed by a junior designer with non-maintenance background be trustful? Can an experienced mechanic perform a simulation on an immersive environment with no withdraws? How these analysis can be fed back to the PDP and serve the project along the complete development?

Important issues that need better understanding before deciding which environment shall be used – immersive or non-immersive.

2.5.10 Analysis databases

Peng *et al.* (2012) propose a VR-based visualization system in order to share CAD data among different project players. By that, maintainability analysis performed by technicians can be flowed to Product Designer serving as feedback during PDP (see Figure 2.28). All the analysis material, from the actual CAD models up to the maintainability analysis results will be tagged in the XML files proposed by the authors.

As normally CAD systems do not include maintainability features information, Ding (2009) created a product feature classification within Solidworks. There, Maintenance has been included as one of the important product features (See Figure 2.29). Designer may include/store data such as maintainability qualitative demands, maintenance resources, maintenance process, targets (e.g. MTTR), among other data. All these data may be reached from the database whenever development engineer needs such information. However, it is not clear who would transfer the maintenance knowledge to the system and how this information could be used in a clever way to support product development.

Again, these databases methods rely too much on Field Test Engineers/Technicians with their expertise to review a work which has already been performed by the Product Designer. They do not support CAD specialists to think about maintenance when product is being designed.

2.5.11 Path planning

Aguinaga, Borro and Matey (2007) have proposed a methodology in which path-planning are presented in order to simulate disassembly tasks (tightly connected to maintenance activities). Authors claimed that their method is capable of performing a disassembly sequence for models with medium complexity in a short period of time (less than two minutes). If the designer interacts with the system by selecting a specific component or area to be analysed time could be reduced. Figure 2.30 shows a simulation of a filter disassembly procedure.

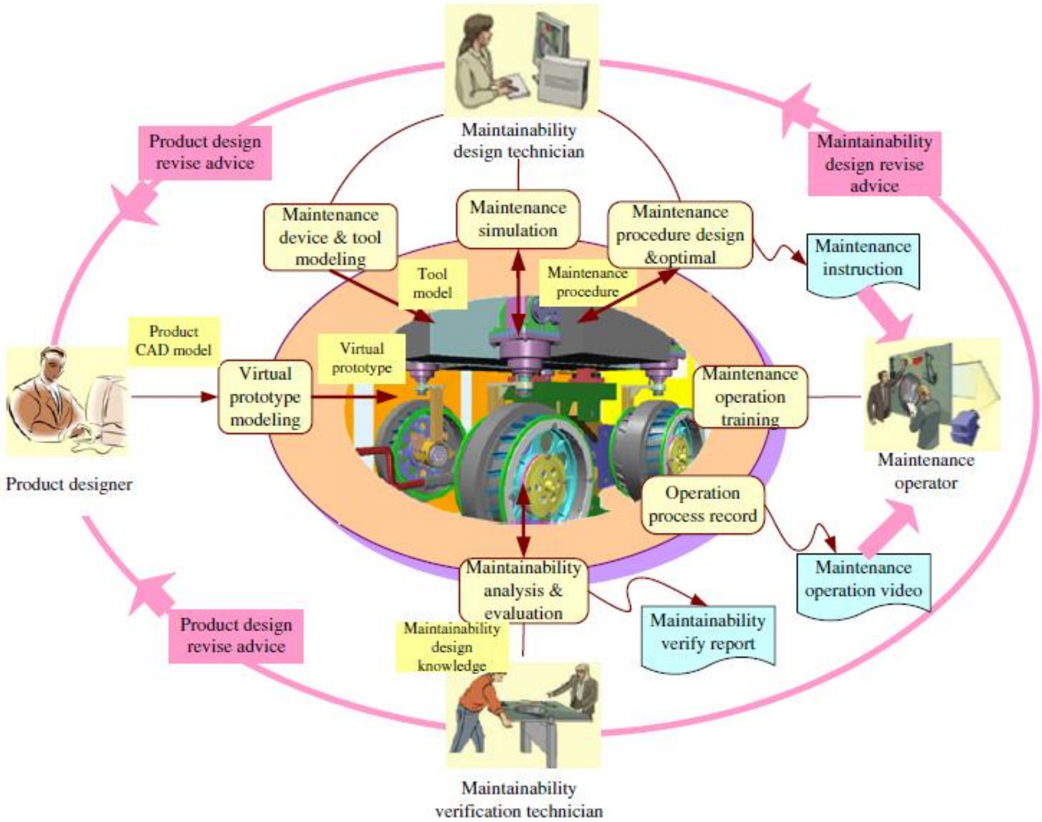


Figure 2.28 – The framework for supporting maintainability design and evaluation at design stage.
Source: Peng *et al*. (2012).

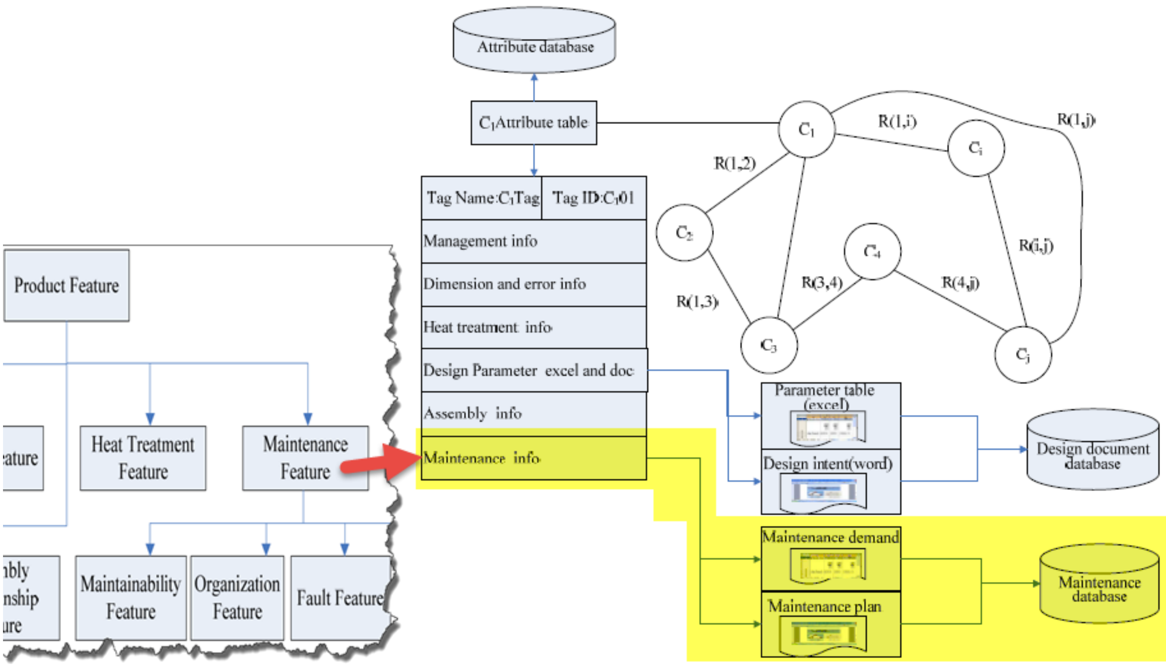


Figure 2.29 – Maintenance feature
Source: Adapted from Ding (2009).

In the given example from Figure 2.30 it is complicated to judge the solution once the filter concept did not present many barriers along the filter exit path.

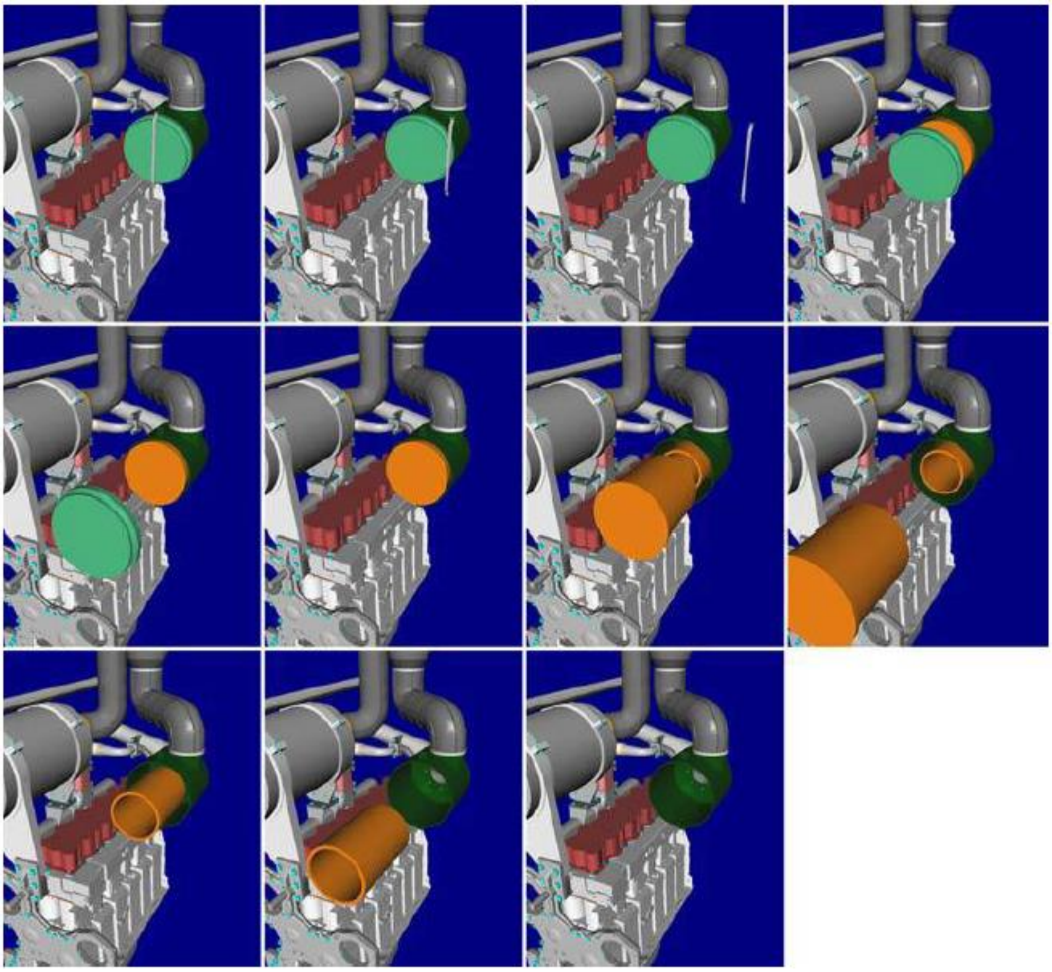


Figure 2.30 – Filter disassembly sequence
Source: Aguinaga, Borro and Matey (2007).

2.5.12 Ergonomic analysis tools

Some tools have been developed to focus on ergonomic and assembly focus. Two examples brought here are DELMIA and IMMA.

2.5.12.1.DELMIA

Even though DELMIA (developed by Dassault Systemes) has been developed towards manufacturing, several authors are using this tool to support maintainability analysis. Some aspects of maintenance reviews can be obtained by using such software (human factors):

a) Ergonomic analysis: RULA (Rapid Upper Limb Assessment) is an ergonomic technique used to evaluate human positions, muscle activities and forces applied during a task/posture (GENG *et al.*, 2013). Figure 2.31 shows a lower mounting position with the operator having to fold his knees in order to fasten a component. A RULA analysis example is given, and the colours (see Figure 2.33) indicate how good or bad the posture is. Figure 2.32 is another example of posture with a Rula analysis presented;

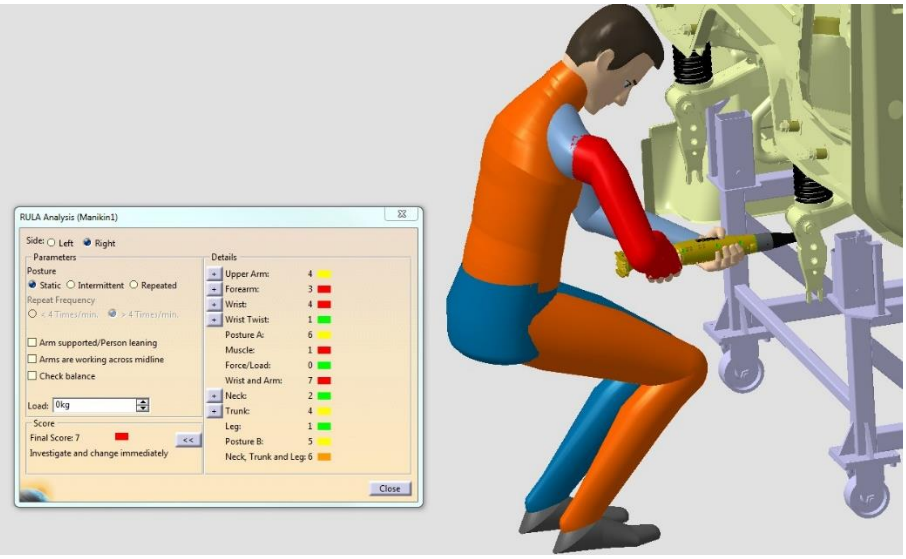


Figure 2.31 – RULA score and position analysis (DELMIA)

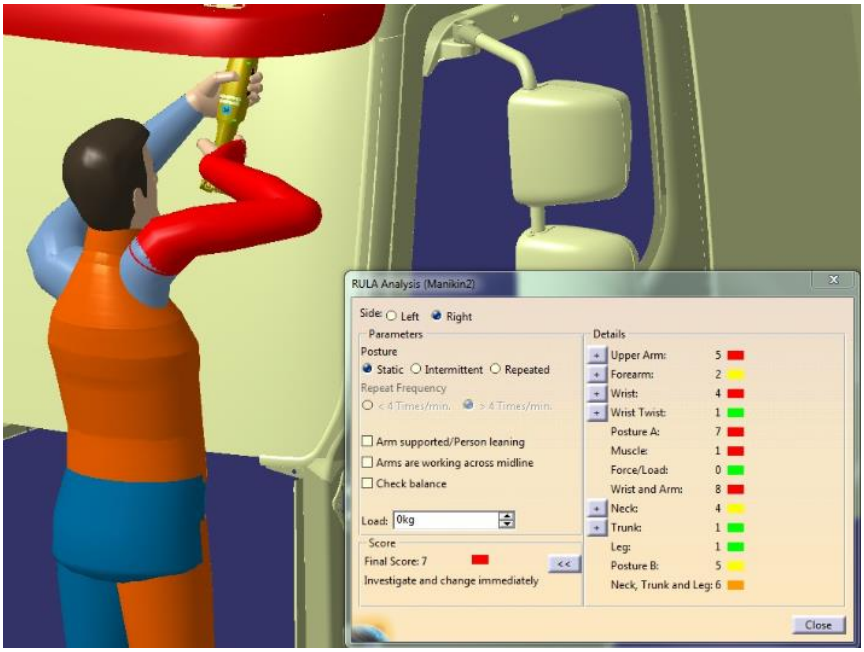
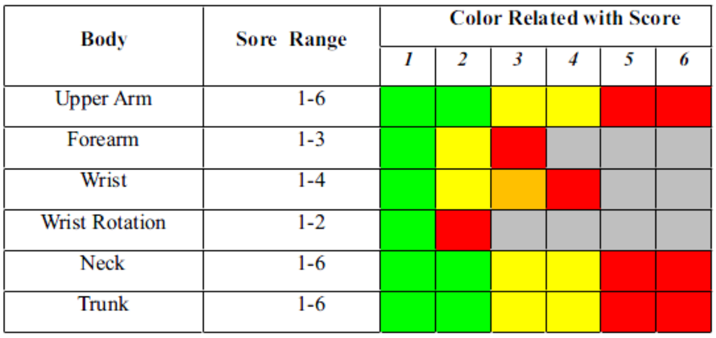


Figure 2.32 – Ergonomic analysis (RULA)



Body	Sore Range	Color Related with Score					
		1	2	3	4	5	6
Upper Arm	1-6						
Forearm	1-3						
Wrist	1-4						
Wrist Rotation	1-2						
Neck	1-6						
Trunk	1-6						

Figure 2.33 – RULA score (DELMIA)
Source: Geng, Shi, Zhou (2011).

b) Visibility: with a pre-defined worker position it is possible to evaluate his vision. Figure 2.32 shows an operator mounting a truck cab sun visor, as on Figure 2.34 it is possible to observe his vision when simulating such operation. Figure 2.35 shows another example of maintenance operation;

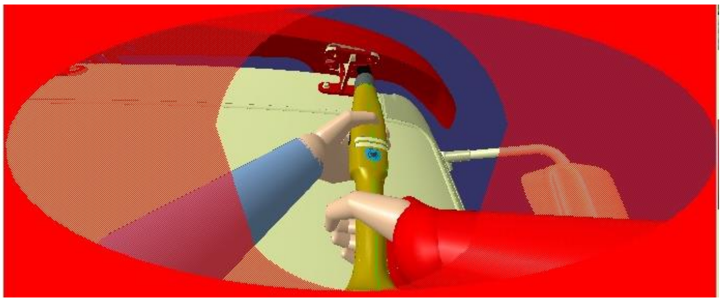


Figure 2.34 – Vision area of a cab sun visor mounting procedure (DELMIA)

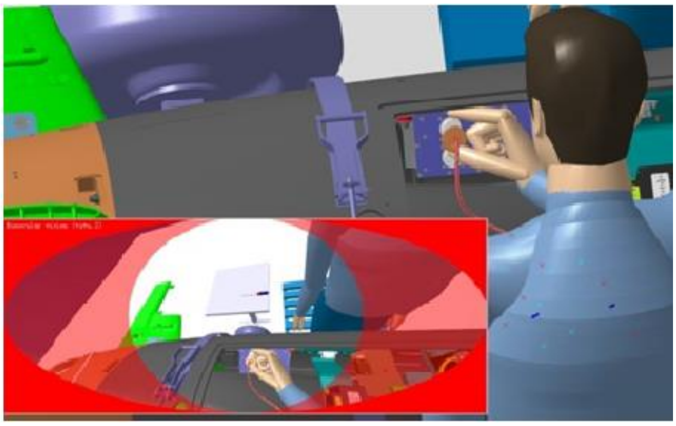


Figure 2.35 – Maintenance operation and corresponding vision display (DELMIA)
Source: Geng, Shi, Zhou (2011).

c) Reachability: with the human manikin it is also possible to evaluate if a component is reachable or not by the operator (See Figure 2.36) and if there is enough space for the operation to occur.

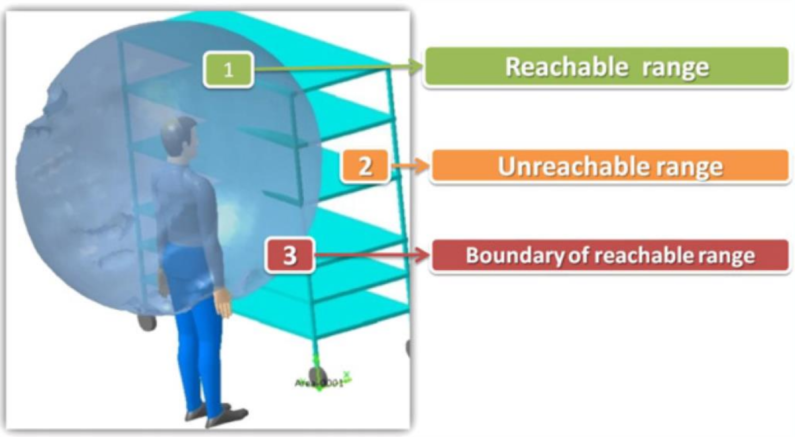


Figure 2.36 – Reach envelope of an arm (DELMIA)
Source: Geng *et al*. (2013).

2.5.12.2.IMMA and IPS

From an assembly perspective feasibility, Hansson, Högberg and Söderholm (2012) have applied IPS and IMMA tools (developed by Fraunhofer-Chalmers Centre) to simulate a carpet assembly into a truck cab from Scania. IPS was used to find a collision free route for the carpet assembly. It delivers a motion trajectory, a sweep volume of such movement as well as the shortest distance to the surrounding environment as results (see Figure 2.37).

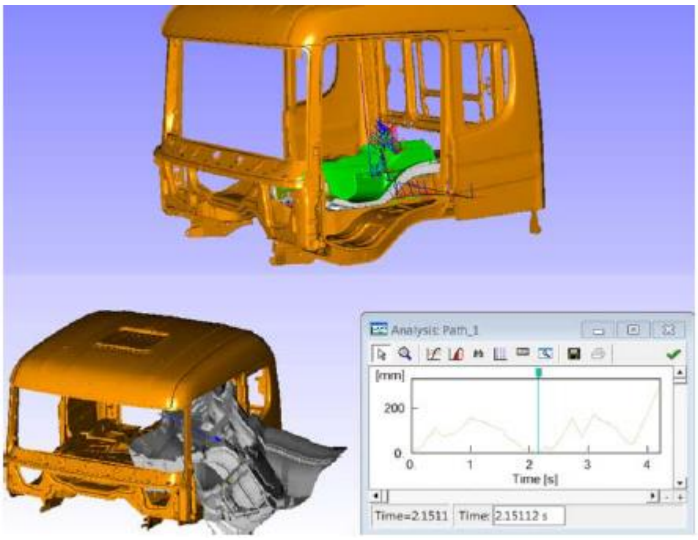


Figure 2.37 – IPS tool
Source: Hansson, Högberg and Söderholm (2012).

And IMMA (Intelligently Moving Manikins) is used to simulate a manikin assembling the carpet by using the same path proposed in IPS to accelerate assembly simulations. Ergonomic analyses are then performed to validate or not the quality of working positions when performing this task.

Lövgren and Andersson (2012) emphasize that most tools existing today for digital human simulations are based on static posture analysis. In IMMA the application of path planning techniques to generate collision free routes (IPS) and biomechanical acceptable motions improve simulations and also reduces the level of expertise necessary to conduct such ergonomic analyses. The user can define a volume (Figure 2.38) in which the path planning will occur. This reduces the space in which IPS needs to calculate the exit path for the screw on Figure 2.38 for instance.

Evaluations involving industrial partners (AB Volvo included) were being conducted to collect feedback and to improve even further the tools. Nothing on maintenance side is mentioned though when using IPS/IMMA, even though they could be used in this sense as well.

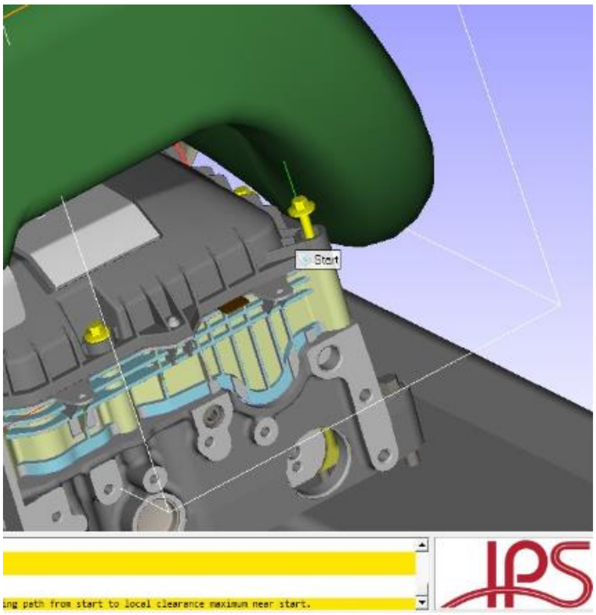


Figure 2.38 – IPS volume of analysis

2.5.13 Virtual maintenance analysis Pro-E plug-in

Besides proposing a Positioning Indicator (see section 2.5.3) using Wave Propagation method, Moscheto (2009) also suggested other tools to enhance Maintainability analysis within PDP. In fact, a complete model to apply maintainability parameter in PDP was proposed in the study as presented by Figure 2.39. "*The concept of this model has evolved, based on the PDP phases proposed by Pahl et al. (2005). The structure of the model can be mapped to the CAD modelling evolution suggested on*" Figure 2.11 (MOSCHETO *et al.*, 2017).

A plug-in was developed in Pro-E (with Pro/Toolkit libraries and C language) with three different possibilities: i/ Golden components (see section 2.5.13.1); ii/ Product Composition; iii/ Fasteners (see Figure 2.40).

The tool was mostly developed specifically for designers working on the conceptual and embodiment design phases to create a certain independence from experienced service engineers (called as product support engineer on Figure 2.39).

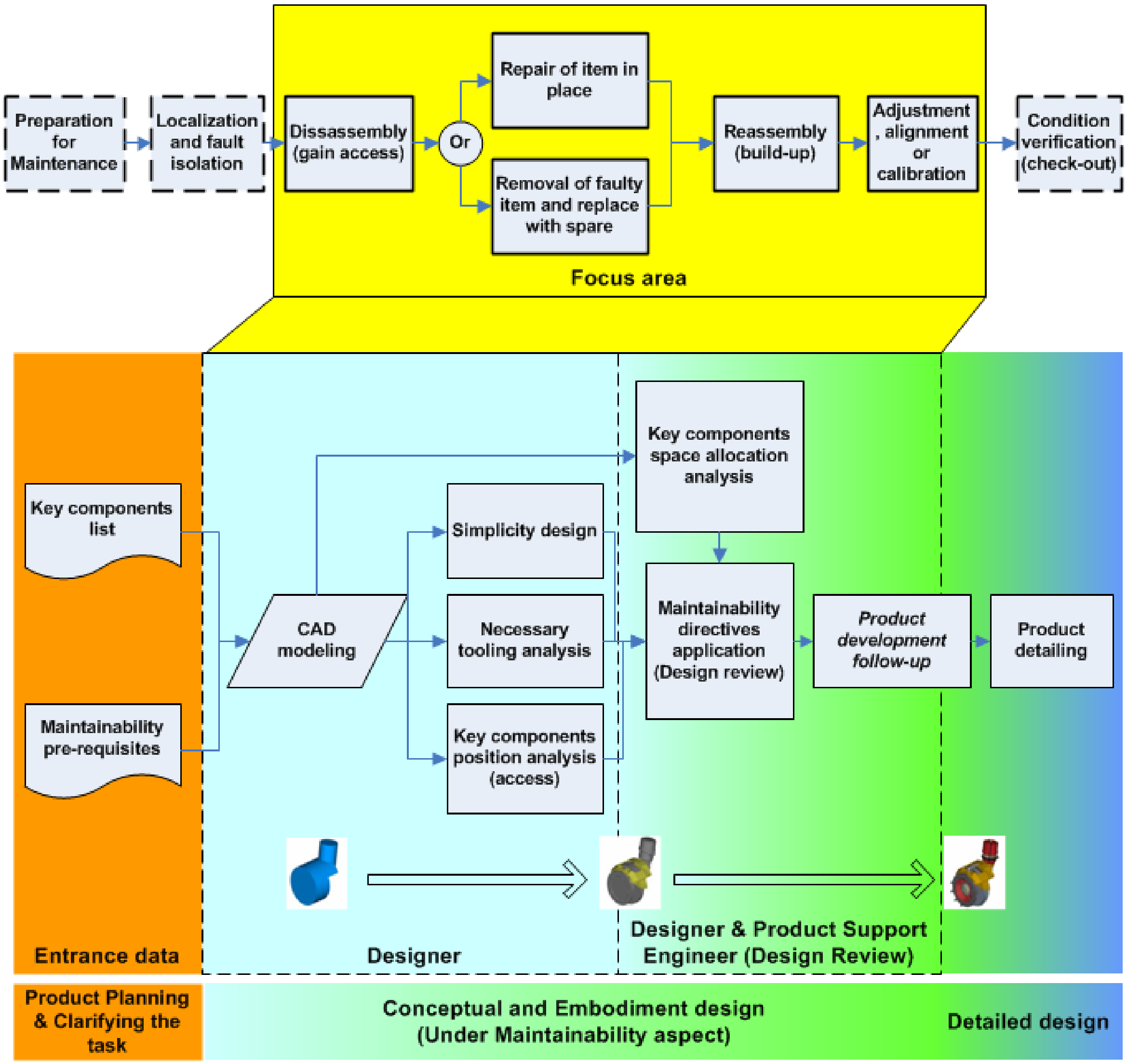


Figure 2.39 – Model to consider maintainability parameter in PDP
Source: Adapted from Moscheto *et al.* (2017).

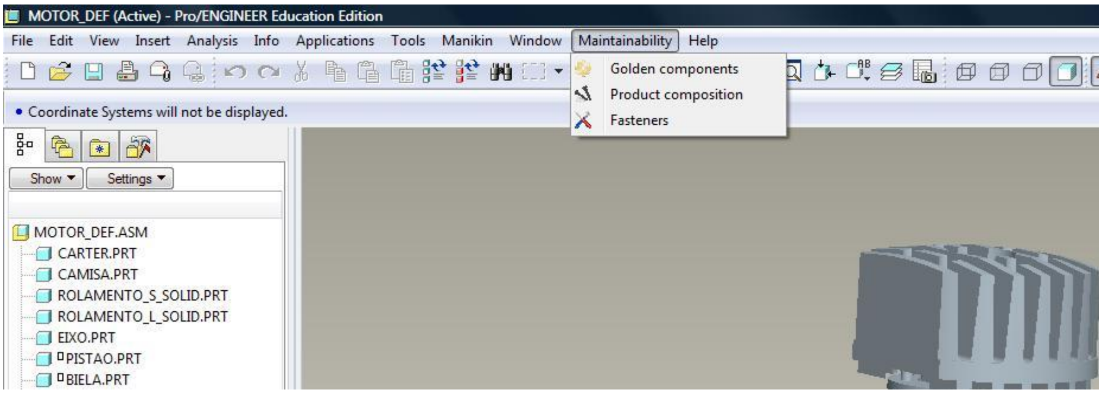


Figure 2.40 – Pro-E Plug-in pull-down menu
Source: Adapted from Moscheto (2009).

2.5.13.1.Key components for the aftermarket

Key-components were called as **Golden components** by Moscheto (2009) due to their relevance to the aftermarket and obviously to maintenance activities. In the literature such components are also called as **Critical components (**BLANCHARD; VERMA; PETERSON, 1995). The idea when selecting golden components in the plug-in was to seek (Figure 2.41) for all relevant parts via their nomenclature and/or part numbers and highlight them (Figure 2.42) to the designer, sending a clear message of which components should be prioritized in their maintenance analysis.

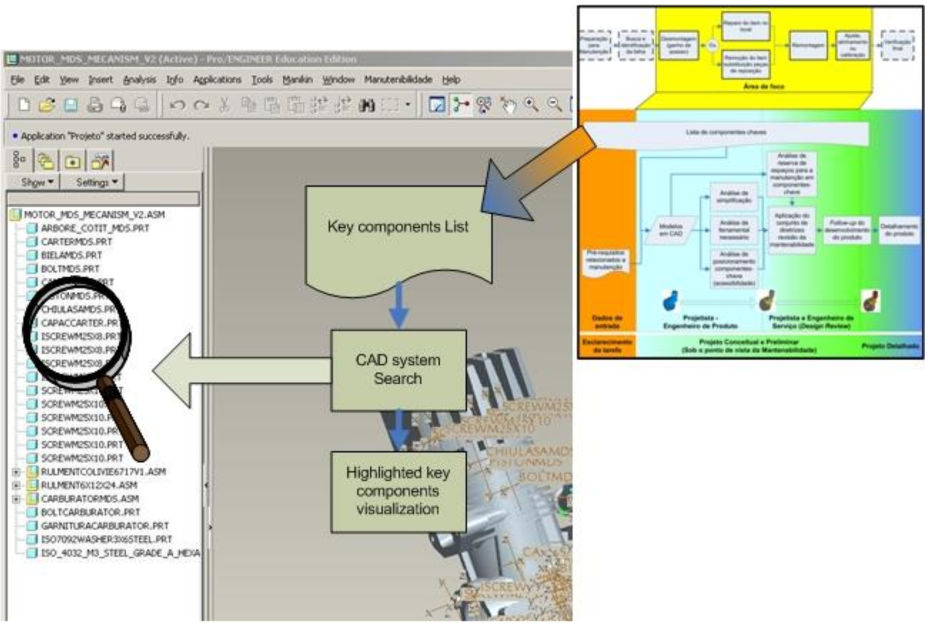


Figure 2.41 – List of components in CAD systems
Source: Moscheto (2009).

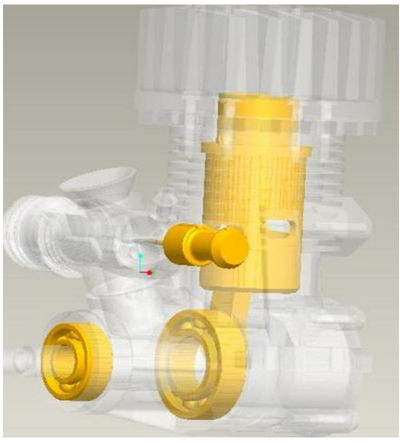


Figure 2.42 – Highlighting project's key-components
Source: Adapted from Moscheto (2009).

Based on key-components, later on in the development process when a more mature 3D virtual product is available, product designers would count on the experience from service engineers to give their inputs via space claiming (Figure 2.43). Basically, field knowledge (e.g. tool usage, service tips, importance of the task) and ergonomic aspects are frozen in a 3D swept volume. Such volume is used then by CAD specialists (designers) to evaluate possible interferences (Figure 2.44).

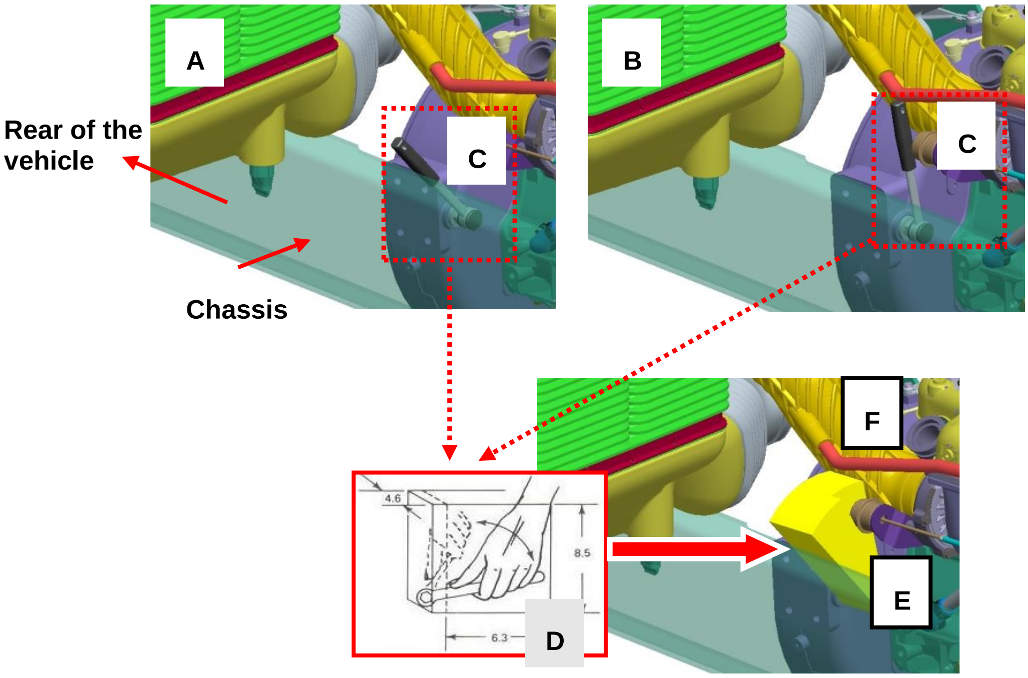


Figure 2.43 – 3D-space claim to facilitate product's maintenance
Source: Moscheto (2009).

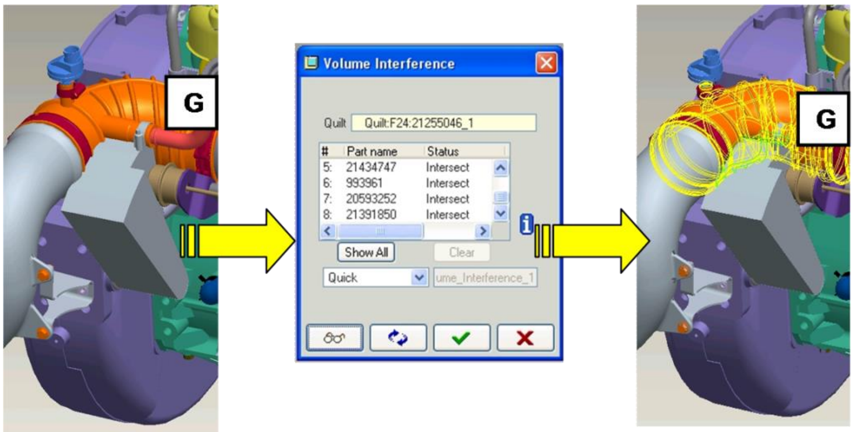


Figure 2.44 – Interference analysis in space claim for maintainability – engine case study Source: Moscheto (2009).

Another example of space claiming analysis is presented on Figure 2.45 for a clutch disc replacement, in which the gearbox removal path is recorded to simulate all clashes with different components.

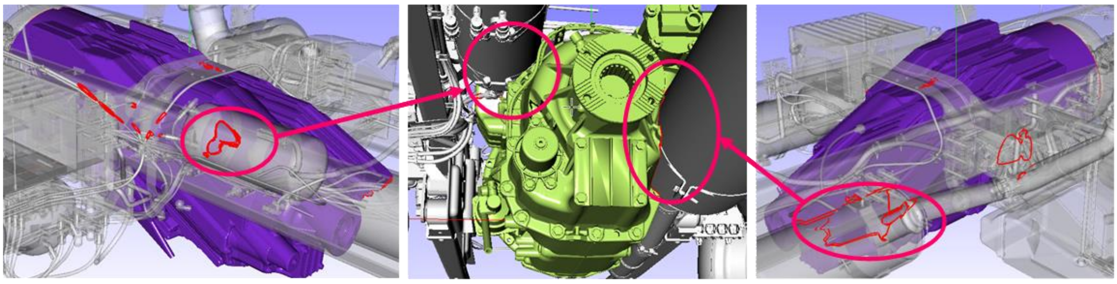


Figure 2.45 – Interference analysis in space claim for maintainability – gearbox case study Source: Moscheto *et al.* (2011).

Moscheto *et al.* (2017) brought strong business cases from the examples explored on Figure 2.44 and Figure 2.45. They deeply support the idea of using space claiming in the development of complex products once “*this method optimizes the shortfalls such as higher repair time, complex training, constant creation of special tools and bad ergonomic service solutions*”.

Even though space claiming model based on golden components are a major enhancement on PD for maintainability reasons, this concept is fully reliant on field expertise. By the moment a space claim is formed/proposed a lot of engineering hours have already being spent in order to bring a 3D model with the minimum maturity level needed for such analysis. That is why on Figure 2.39 space claiming step (declared as “Key components space allocation analysis”) is presented on a later phase in PDP. If a space claim brings major design changes development costs are in fact raised.

Therefore, it is still desirable to improve the way designers understand and apply the maintainability parameter in PD. For that, Moscheto (2009) also proposed two other functions to boost maintainability consideration in CAD developments, Product composition and Fasteners options in the PTC Pro-E plug-in.

2.5.13.2.Product composition and fasteners

On Product composition (Figure 2.46) designer is able to compare product under development to the company’s parts inventory (called as “Simplicity design” on Figure 2.39). In other words, the CAD specialist is able to understand the level of new parts he/she is adding to the inventory as well as to comprehend what are the standard parts being re-used from earlier projects/products.

As for the fasteners option (Figure 2.47) in the plug-in (“Necessary tooling analysis” on Figure 2.39), the idea presented by the author was to seek for all fasteners available in a golden component by their nomenclatures. The steps used on this function are (MOSCHETO, 2009):

a) *“From the part’s nomenclature, the system captures its main features. The fixing element mandatorily needs the termination _Y_MDXC, where Y is the character that indicates the screw-head’s type, D represents the thread diameter and C is the screw’s length (e.g.: SCREW_F_M12X8.prt represents a split-head screw, M12 thread and length of 8 mm)”;*

b) *“To calculate the number of tools, only the characters Y and D are considered to compile all possible screw heads/threads in the model. The number found by the search will result in the proposition of a number of universal tools necessary to repair the product”;*

c) *“The times estimated to remove and install fixing screws/nuts are calculated from the multiplication of the time proposed in Table 2.1 by the quantity of each element the model finds”.*

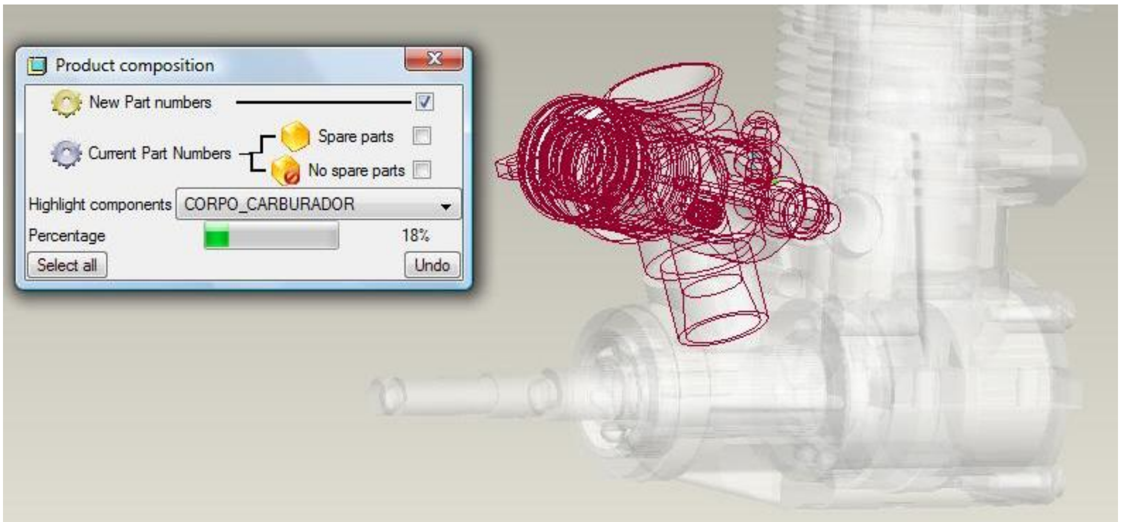


Figure 2.46 – New parts selected in the maintainability tool
Source: Adapted from Moscheto (2009).

By using such methodology, it would be possible to standardize the product selecting fasteners of the same type and, preferably, of the same size, minimizing the number of tools to be used.

With the tool (Figure 2.47), even if the development team has no experience in performing product maintenances, CAD system will indicate a high number of tools to-be-used or a relatively high assembling/disassembling time for a set of screws, and display a strong message on the possible difficulties the mechanic will face to implement the service operations.

The final purpose is to give real-time feedback to the design engineer resulting in modelling modifications, to a simpler and more standardized fasteners concept. **One drawback of this proposal though is that there is no consideration on the difficulty to assemble/disassemble the fastener.**

2.6 Opportunity Identification and reasons to investigate

Leon *et al.* (2012) divided the maintenance literature review in two different groups:

a. "Expert based methods using the experience and insights of maintenance experts";

b. "Statistics based methods applied to historical data recorded from trials".

By reviewing several papers from different journals and classical literature it is clear that most of the maintainability analysis (immersive and non-immersive) are highly (if not totally) dependable on very skilled service personnel. Lv, Zhang and Wang (2013) who believed that current maintenance design mainly involves the experience approach, mostly with qualitative requirements, also confirm this.

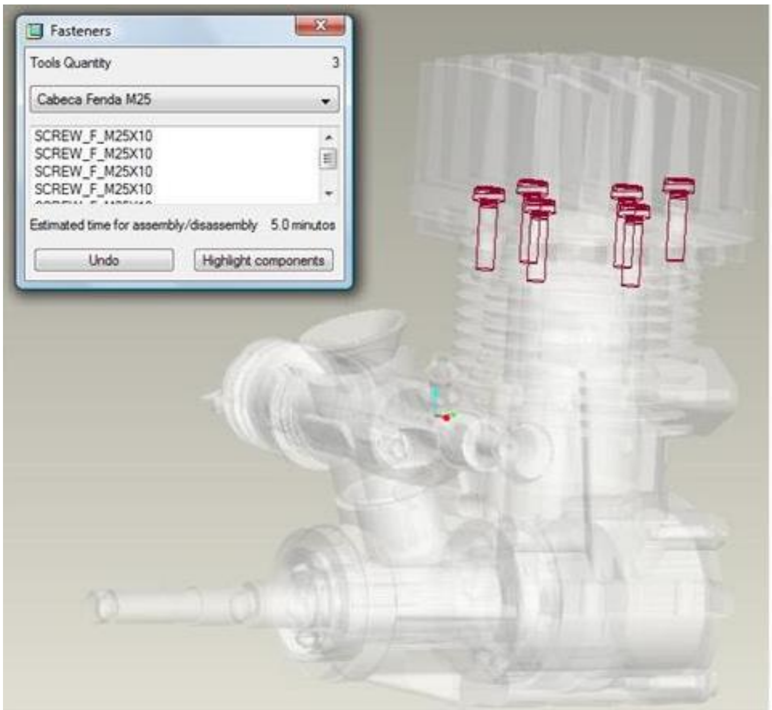


Figure 2.47 – Plug-in fastener function
Source: Adapted from Moscheto (2009).

From another point of view, some methodologies try to perform automatic analysis (through mathematical algorithms) either with a lot of previous manual work/thinking or with poor end results (loopholes), which cannot be used in practice by developers.

The classical literature, in spite of constantly mentioning use of CAD systems, long checklists and referring the goals to be achieved (e.g. MTTR), barely presents real guidance on how to connect all maintainability knowledge into today's virtual product development. Moscheto (2009) proposed a set of tools that try to advance some steps further to help designers to properly address this parameter in PDP giving some kind of freedom from deep field experience. However, there are still drawbacks that need to be addressed (such as fasteners accessibility).

To find engineers with good expertise on CAD systems, product development and service expertise is not an easy task, and to develop someone with such proficiency obviously takes time.

It is clear then that there exist gaps hindering PD to properly develop product thinking on maintainability. Approaches that overcome field experience, by helping designer to take into account maintainability directives right on spot (in the very moment product is being created), will not only enhance final product's maintenance, but also reduce substantially rework levels on PD virtual development.

2.7 Maintainability gap in PDP

As discussed along the entire Chapter 2, the main limitations for maintainability analysis on current researches available are the impractical usage of some mathematical algorithms and high dependency on service experience on most virtual maintainability analysis proposals reviewed.

On the maintainability evaluations presented along Chapter 2, Accessibility and Ergonomic analysis formed two maintainability analysis commonly used. For Accessibility three human factors were extensively examined: i/ visibility; ii/ reachability; iii/ access space. As for Ergonomic Design, RULA methodology was the factor most commented/investigated/used.

By observing RULA concept, it is understandable why this tool is so popular. As soon as the manikin position is defined, it is fairly simple to run a routine which generates an outcome, expressing how good or bad the worker position is. With its colours, it sends a clear message on what is weak in the solution being proposed by the designer (on the ergonomic aspect).

Visibility, reachability and access space have been the human factors mostly evaluated by several authors under maintainability analysis. As they are intimately connected to ergonomic analysis, it is reasonable that tools such as DELMIA and IMMA, simulating a human manikin, have been used for such purposes as well. However, no matter if the analysis would be conducted on an immersive or non-immersive format, it could demand a lot of analysis to conclude if the key-component (golden component) position would be satisfactory or not from a maintainability point of view.

Thus, could a model support the development engineer with automatic maintainability evaluations? Configuring a scenario for maintainability analysis, one should examine the example given on Figure 2.48. An engine valve cover is considered a golden component because on regular basis mechanics need to perform valve adjustments (preventive maintenance). The 3D model is already mature enough for a maintainability analysis. This is a real example in which the developer has delivered a concept for maintainability evaluation.

By taking a closer look at the concept supplied Figure 2.49 shows a simulation with a star spanner on the initial position (Figure 2.49 **A**) and at the end of the screw tread (Figure 2.49 **B**). Figure 2.49 **C** shows that there is not enough space to remove the complete screw length. If this would be a final solution provided by the design office, inlet system duct would have to be removed in order to perform a valve adjustment.

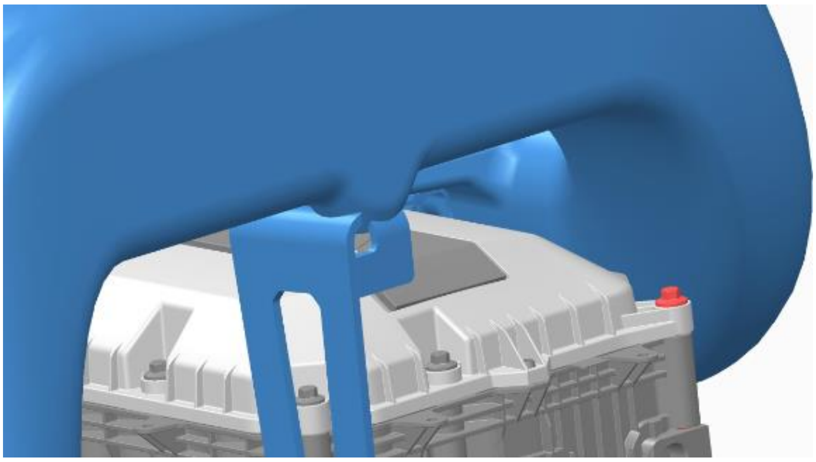


Figure 2.48 – Engine valve cover

Going further in the analysis, Figure 2.50 shows the same example but now with a ratcheting wrench (Figure 2.50 **B** is the final screw tread position). As this tool is commonly available (and used) in the market because it is quicker to unscrew fasteners (time gains), the solution becomes even worse. Additionally, if taking into account that all valve cover screws should be torqued with a torque wrench, it becomes even clearer that a very poor solution has been provided.

It is important to highlight that the tool and hand movements should also be examined in the analysis (see Annex A, Figure AN.1 to Figure AN.3). Since on the valve cover example it is already impossible to remove the screw with its own length, such evaluation becomes worthless.

To evaluate this scenario, either in an immersive or non-immersive method, it would be very time consuming to reach this conclusion, as on the same valve cover there are several other screws.

Another example, an air compressor from the same engine (Figure 2.51) provides further insights. A removal path was calculated using IPS (Figure 2.52 and Figure 2.56). Fuel lines are in the way in the compressor exit path detail **A** (Figure 2.51).

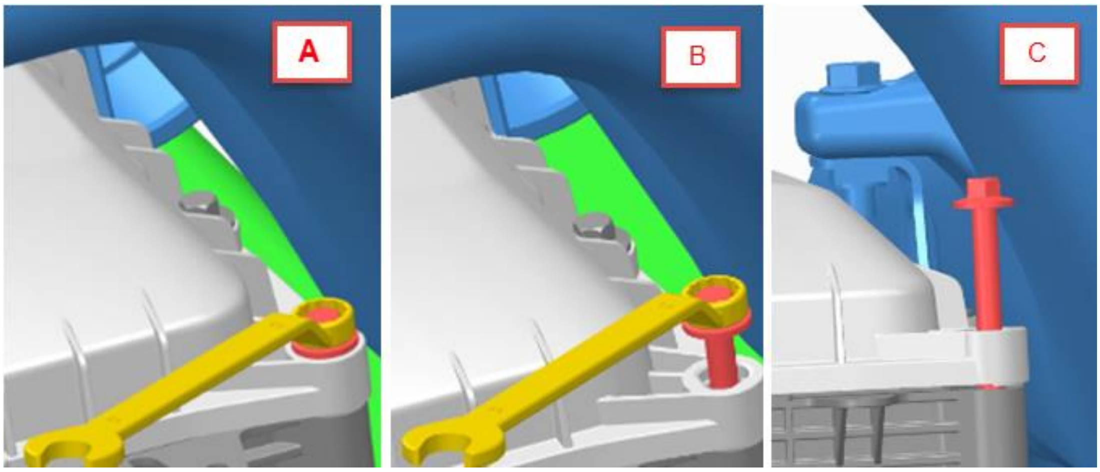


Figure 2.49 – Engine valve cover: star spanner analysis

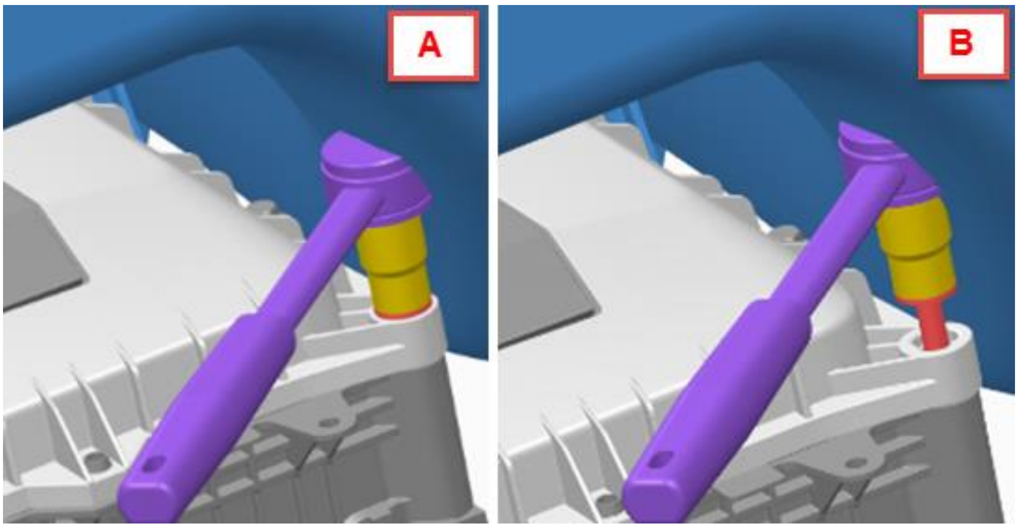


Figure 2.50 – Engine valve cover: ratchet wrench analysis

In the compressor example, it is possible to note that not all fasteners are visible (arrows **B** in Figure 2.53). Beyond that, there could be issues with reachability and access space as well. For one screw, a ratcheting wrench with a socket is needed (arrow **C** in Figure 2.54), even though it is already possible to see interference with fuel lines.

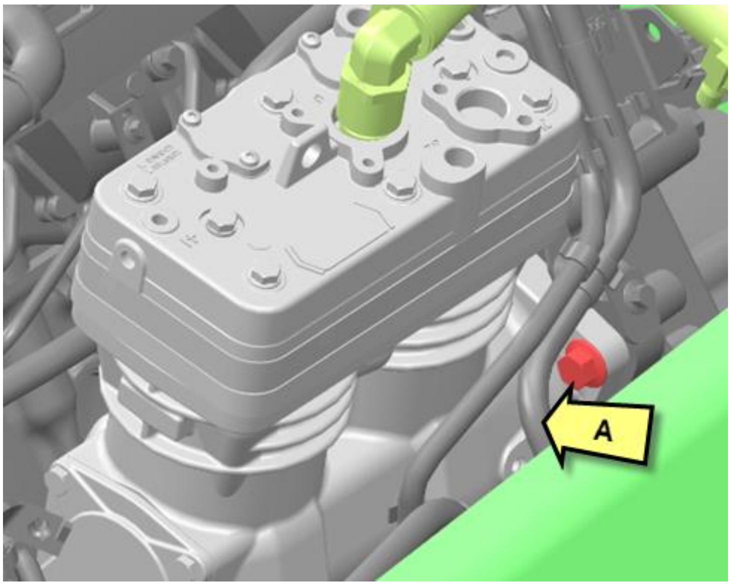


Figure 2.51 – Air compressor fully installed

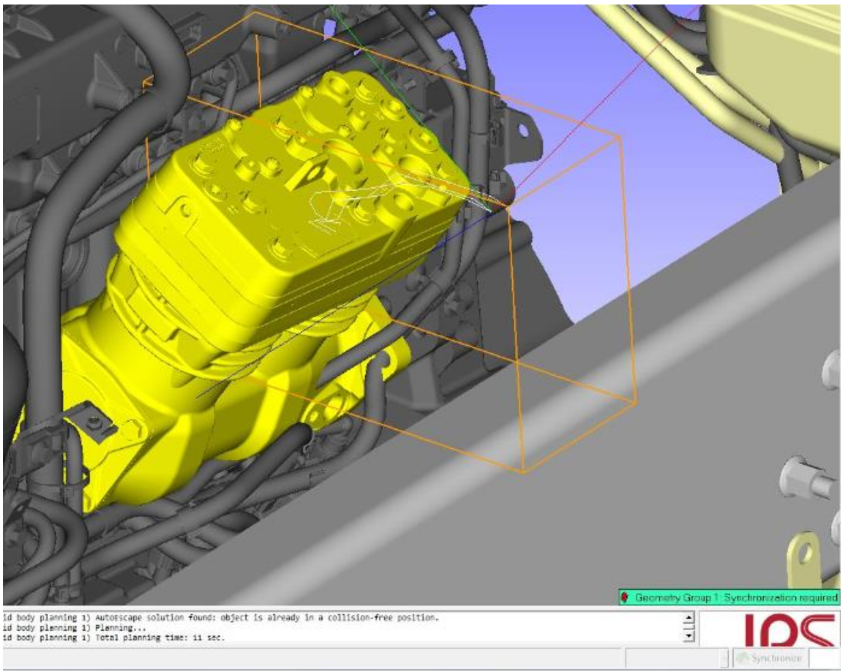


Figure 2.52 – Air compressor removal path in IPS

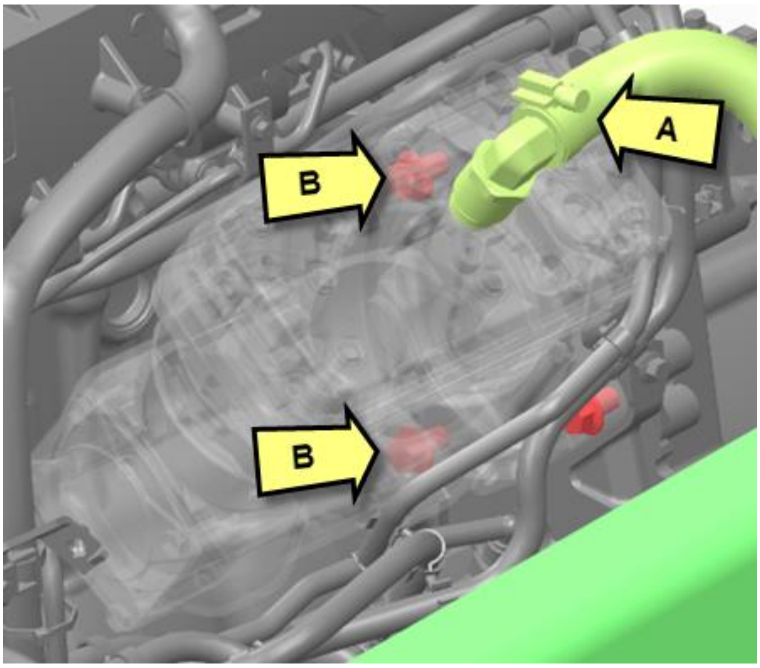


Figure 2.53 – Compressor hidden fasteners

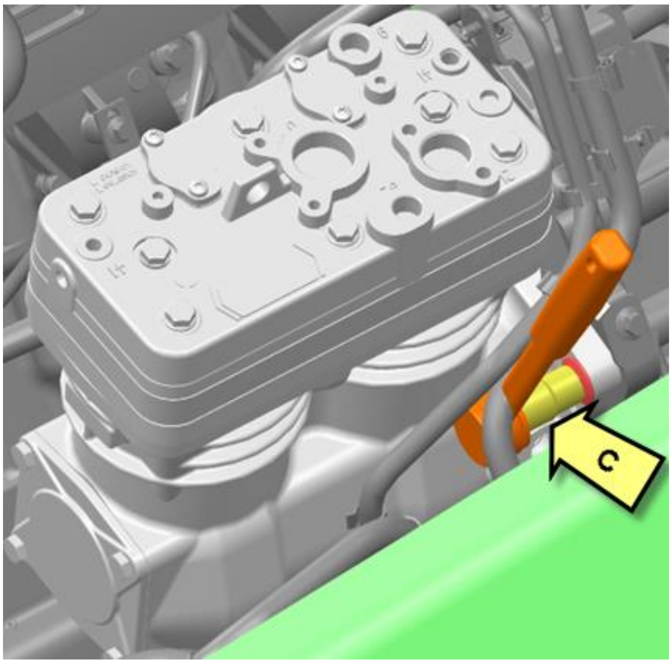
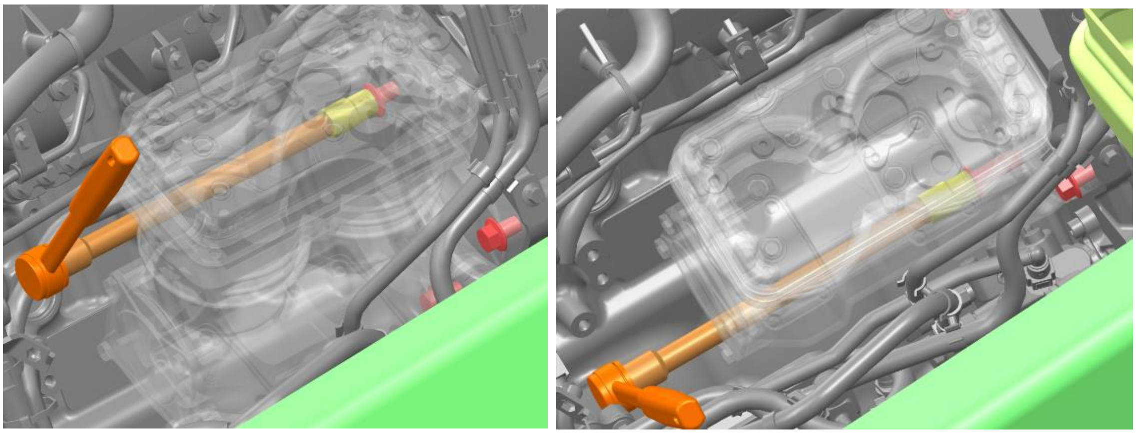


Figure 2.54 – Interference between tool and components

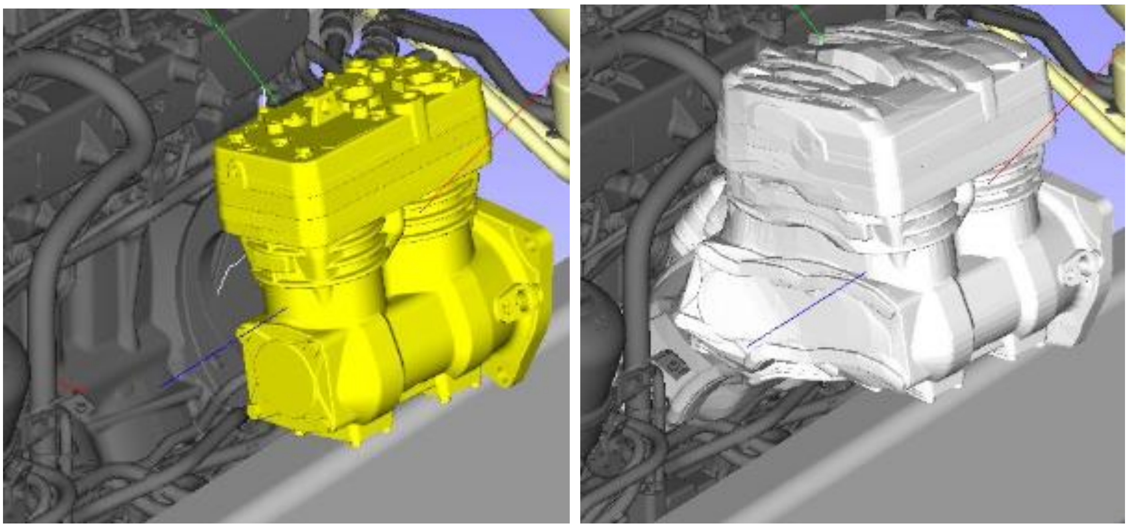
For the remaining two screws, just a ratcheting wrench and a socket are not enough: an extension bar is also required (Figure 2.55 **a** and **b**).



a/ Ratcheting tool: position 1 b/ Ratcheting tool: position 2

Figure 2.55 – Compressor fasteners: extension bar required

Then, after removing fuel lines (and the pneumatic hose presented by arrow **A** in Figure 2.53 – which is natural to occur) and the actual fasteners, IPS was able to calculate a removal path and to create a space claiming (Figure 2.56 **a** and **b**).



a/ Removal path calculation b/ Volume needed to remove the compressor

Figure 2.56 – Compressor removal path and space claiming

2.7.1 Steps necessary to evaluate fastener analysis

Reviewing then the steps that were necessary to evaluate both examples just presented:

1. Golden component was defined;

2. Which fasteners are visible or not;
3. Evaluation on the accessibility and reachability to remove all fasteners (depending on the fastener types, different tools could be required);
4. Interferences were found inhibiting fasteners removal. Parts have to be removed before it is feasible to remove golden component and its fasteners (weak maintenance solution).

Returning to the fasteners option in the plug-in developed (Figure 2.47), there screws would be identified, a database match would tell the number of universal tools re quired (based on the different sort of fasteners applied) and a time frame for their removal would be given (not considering access and the possibility to reach them). As it is very time consuming to analyse reachability and accessibility of all fasteners, it would be very welcome to introduce a tool that could automate such maintainability analysis, helping designers to better address this parameter. Further details of the aimed approach are discussed in the next chapter.

3 MAINTAINABILITY MODEL

3.1 Maintainability model creation

Through the literature review it was possible to identify the opportunities as most of the current maintainability analyses are deeply dependent on very experienced service engineers. To develop an approach (model and tool) that gives some degree of freedom to product designers is highly desirable, as less rework on virtual developments and design reviews would be achieved.

Recovering the thesis objective, a new maintainability model should be developed in a tool/plug-in format being embedded in a CAD system, supporting development engineers to correctly address maintainability parameter during PDP, in an automated way or by guiding them with an integrated checklist.

Referring to fasteners option in the plug-in (2.5.13.2), it is clear that accessibility was a missing feature on it. Therefore, to support designers with a maintainability model which automates the fasteners accessibility analysis would increase their independence in the maintainability evaluations.

3.1.1 Fastener removal – mechanic's view

To further support the maintainability model construction it is very important to understand how a mechanic in practice performs a fastener removal procedure.

Figure 3.2 shows a flowchart that represents the step-by-step fastener removal procedure:

1 Firstly the mechanic has a visual contact – defining which fastener type needs to be removed. Based on the fastener type a tool can be selected. The definition of the tool can rely on three aspects:

1.1. Fastener type: which is the type of the fastener head (examples are given on Figure AN.4 and Figure AN.5 – slotted head, phillips head, hex or allen head);

1.2. Space available: based on the space available mechanic may also select different tools size. Figure AN.1 to Figure AN.3 from Blanchard, Verma and Peterson (1995) propose a minimum space required;

1.3. Possibility to automate: the mechanic may also evaluate the feasibility to use power tools (electric or pneumatic);

2 When releasing a fastener a mechanic will have to deal with three other aspects related to space evaluation (throughout the complete fastener removal by performing approximately eight hand twisting motions – refer to Figure AN.4);

2.1. Hand position, tool position and angle of actuation (twist movement): depending on the tool and/or the manner mechanic holds the tool space needed may change - see different hand positions on Figure AN.3. Next section explores what is to be considered as a good or bad twisting movement;

3 Finally, when the thread is completely removed the mechanic is able to turn the fastener by hand and remove it from the product.

When removing a fastener the angle of actuation is another important fact to be studied in order fully comprehend the fastener accessibility analysis.

3.1.1.1. Angle of actuation analysis

Junior (2015) proposed four different angles of actuation in order to remove a fastener on his study (15º, 30º, 45º and 60º). However, there is no clear reference why these angles were chosen. Figure 3.1 shows examples of the simulations implemented by Junior.

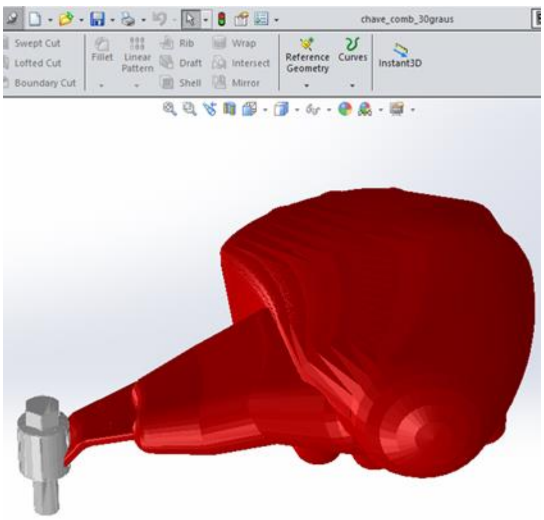


Figure 3.1 – Space claims for screw removal simulation
Source: Adapted from Junior (2015).

Therefore, when evaluating how pleased a mechanic may be by the access of a fastener, the angle of actuation is determinant. Firstly, when selecting the tool size and after by being conclusive on the number of movements that the mechanic will have to perform depending on the angle size.

To confirm these statements and to better understand how a mechanic judges a good access for a fastener removal (angle of actuation) a set of test parts were structured (see Appendix B). The idea was to intentionally block mechanics removal movements on different angles of actuation scenarios in order to collect their feedback on what they consider to be the ideal ergonomic actuation when removing a fastener (on a standstill position). Video[7] presented by Moscheto and Junior[8] shows the concept of these test parts on a simulation before the actual tests with mechanics occurred.

A practical test was performed using the test parts from Appendix B with 13 mechanics. Together with the test a simple survey was applied (Appendix C). Participants had in average 16 years of experience working as mechanics (only males).

In the test, the preferred angle of actuation was from 60º to 75º (both values being selected by five different participants - average of 74º - see Table 3.1), maximum angle of actuation mostly selected were 90º and 120º (average of 96º) and hand position selected was the position 2 (top holding position). See complete survey results on Table 3.1.

Some interesting observations collected from the mechanics during the survey are:

a. Mechanic H was the only left handed in the group and therefore his values were extracted from the average figures. As to unscrew the fastener the movement was against his own body, preferred and maximum angles were both selected as 120º;

b. During the survey it was noticed to be easier to mark the angles (Figure 3.4) and use this as a reference rather than using test part 3 presented on Appendix B;

[7] Videos are used along the entire thesis aiming to present and illustrate the study development. Snapshots were taken from different videos in order to show a sample of the video content as well – giving the thesis reader an option to access or no the referred videos to support his/her understanding on the study content (e.g. Figure 3.3).

[8] Available on: <https://www.youtube.com/watch?v=Prqg3_AhOLQ&feature=youtu.be>. Access on: 05 Sep. 2016.

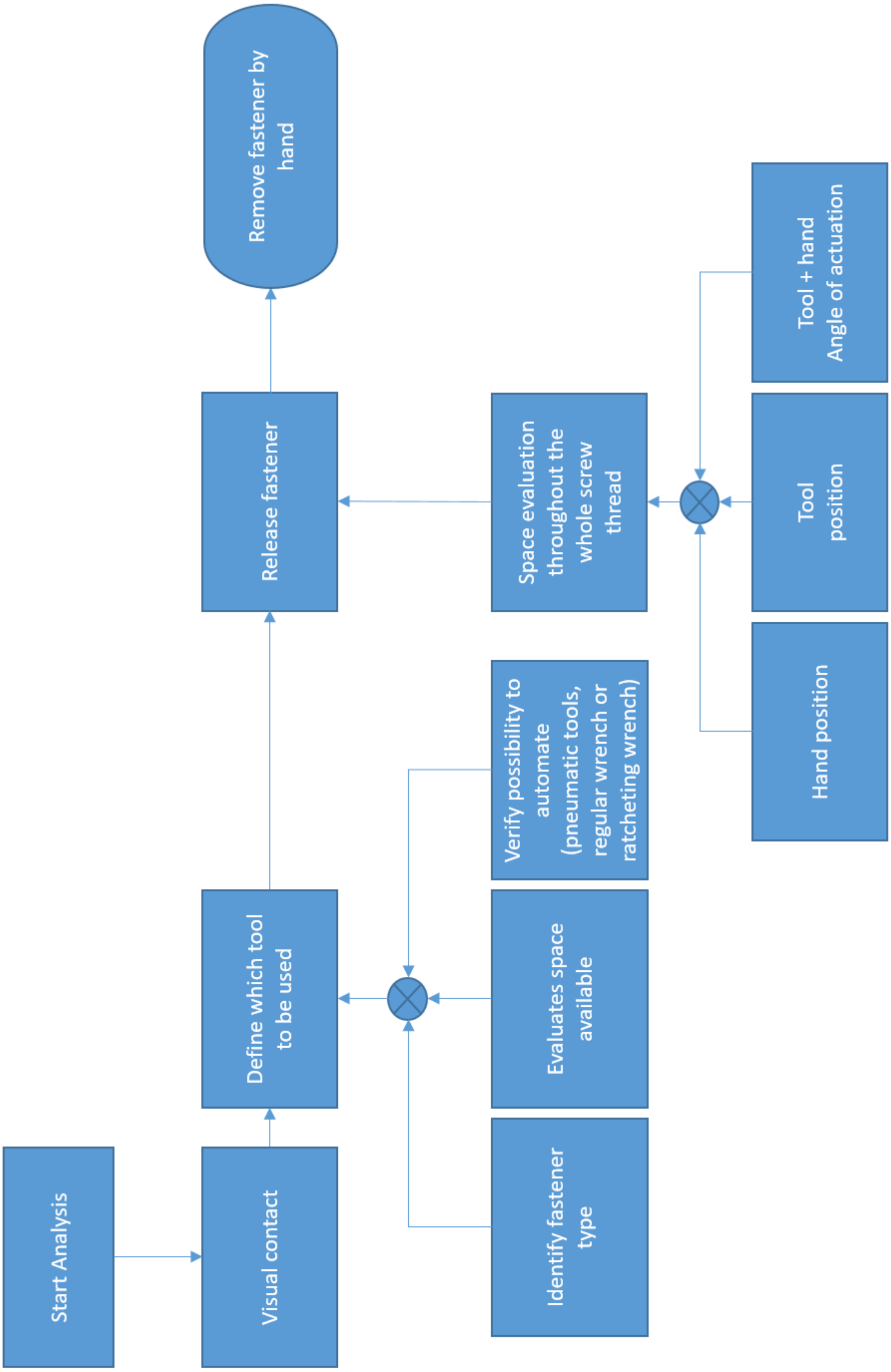


Figure 3.2 – Fastener removal – mechanic perspective

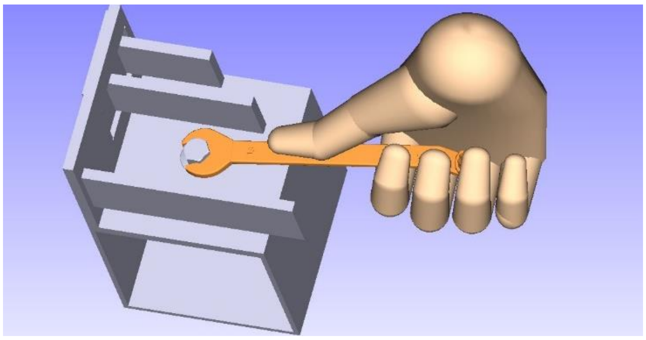


Figure 3.3 – Test part simulation before real evaluation with mechanics

Video[9] “Mechanics’ survey” presents some video samples collected along the survey.

One of the preferred angles of actuation (60º) will be used later in the thesis in the maintainability model (plug-in) to support fasteners removal analysis.

Table 3.1 – Mechanics’ survey on preferred angle of actuation and hand position

						4. When deciding to automate fasteners removal, which criterias do you normally consider? (e.g.: ratcheting wrench, power-pneumatic tools, among others)			
Mechanic	**Age**	**Years of experience**	**1. Practical test - prefered angle of actuation when removing a fastener?**	**2. Practical test - maximum angle of actuation when removing a fastener?**	**3. Which hand position do you prefer when removing a fastener?**	**Space available**	**Number of fasteners to be removed**	**Time gains**	**Other**
Mechanic A	20	0	75	90	2	yes	yes	yes	Torque value
Mechanic B	24	0	75	90	1	yes	yes	yes	Torque value
Mechanic C	26	0	60	60	2	yes	yes	yes	Torque value
Mechanic D	44	24	120	150	2	Yes			
Mechanic E	42	20	60	75	2			yes	
Mechanic F	32	6	60	75	1	yes	yes	yes	Screw path removal is a point to be checked
Mechanic G	36	20	90	120	2	yes	yes		
Mechanic H	43	24	120	120	none - other position	yes			
Mechanic I	53	23	75	120	none - other position	yes			
Mechanic J	53	37	75	120	2		yes		Starts always with a safety analysis
Mechanic K	38	20	60	90	2		yes	yes	Electrical for fasteners smallers. From M8 onwards pneumatic tools are applied.
Mechanic L	54	35	60	75	2				Always enjoy more to apply a manual tool
Mechanic M	23	2	75	90	2	yes			Fastener length is a criteria
Averages		16,2	77,3	98,1					
Average without left handed		16,2	73,75	96,25					

[9] Available on: <https://www.youtube.com/watch?v=o5h-Np-k_Zo&feature=youtu.be>. Access on: 27 Feb. 2017.

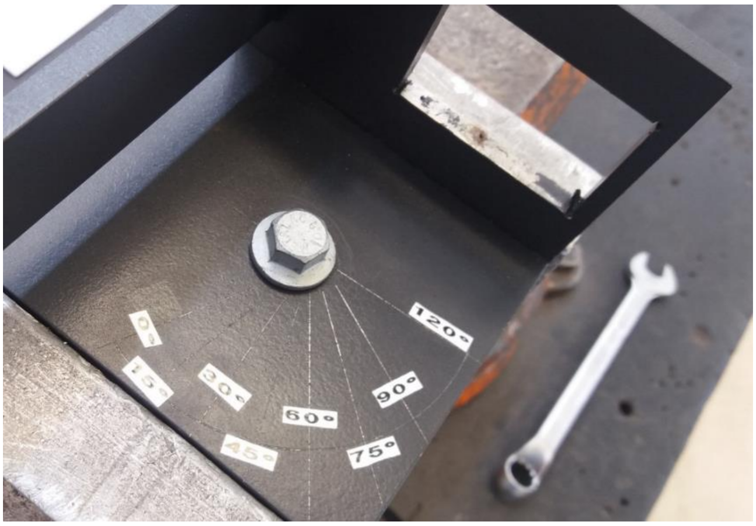


Figure 3.4 – Test component from Appendix B with marked angles

3.2 Maintainability model framework

Recovering the maintainability model (Figure 2.39), Figure 3.5 presents a new flow to be incorporated in the Conceptual and Embodiment Design phases to enhance maintainability analysis for fasteners access under the designer responsibility (before design review and/or support from product support/service engineers).

Basically the model proposes the following steps in the fasteners access analysis (similar to the sequence presented on 2.7.1):

1. By working on a CAD module designer searches for golden components for the aftermarket;
2. Designer needs to seek for fasteners that are hindering the component removal and evaluate their access level;
3. By working on a golden component analysis, designer may apply Maintainability directives[10] to support the component evaluation.

To further explore the fastener accessibility analysis Figure 3.6 presents a complete maintainability module further explaining the steps proposed on Figure 3.5.

Figure 3.7 goes one step further presenting the connections between the model with its details. On Figure 3.8 (section 3.2.1) and Figure 3.9 (section 3.2.2) it is possible

[10] Available on Appendix A.

to explore the Golden Component identification and the Fastener access analysis process flows.

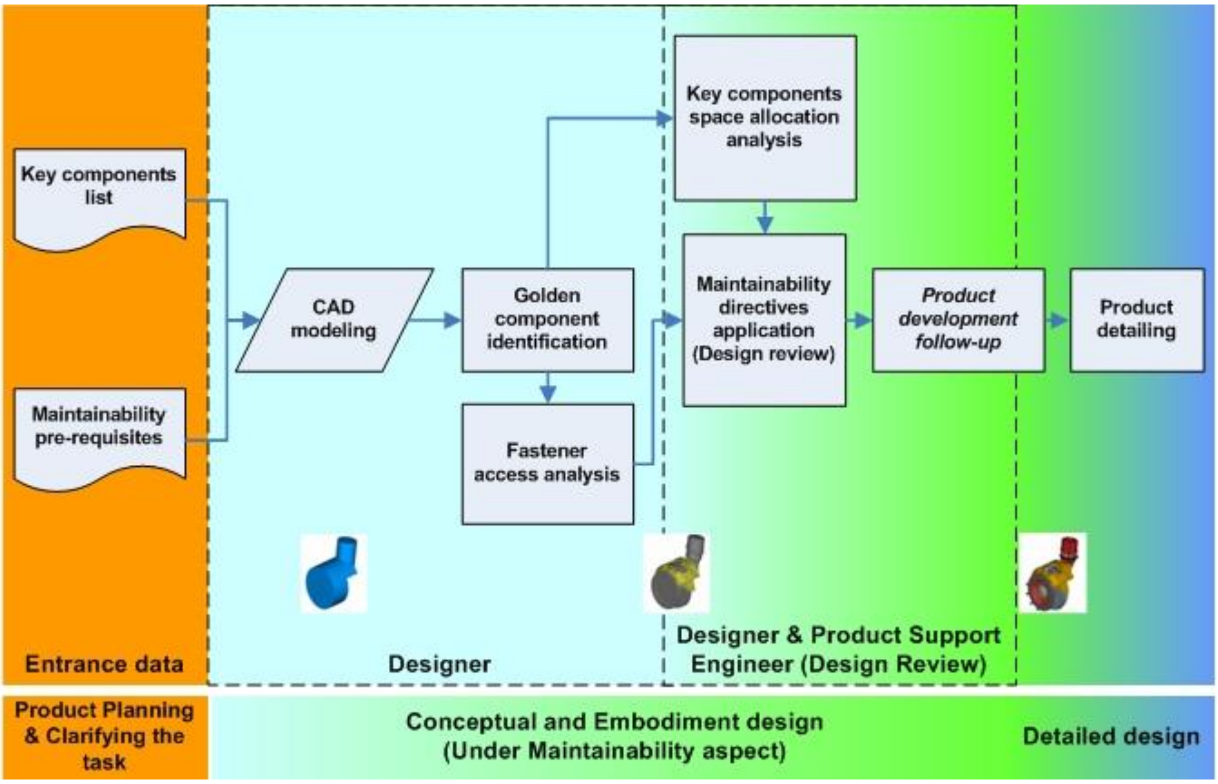


Figure 3.5 – Fastener accessibility analysis flow

3.2.1 Golden componente identification

On the CAD model being created the designer needs to search for the most important components for the aftermarket. The first functionality proposed by the Fastener Accessibility Model is a search (Figure 3.8) that occurs either via parts nomenclatures and/or part numbers (connected to the CAD module/company database structure).

Even though there is no novelty in this function compared to Moscheto' s (2009) initiative, this search procedure is considered to be appropriate to support designers to seek for the important components from a maintainability perspective. By using such approach, designers become less dependent on service experts.

The proposal to highlight the component that is found sends a straight information to the designer of which component has to be aimed.

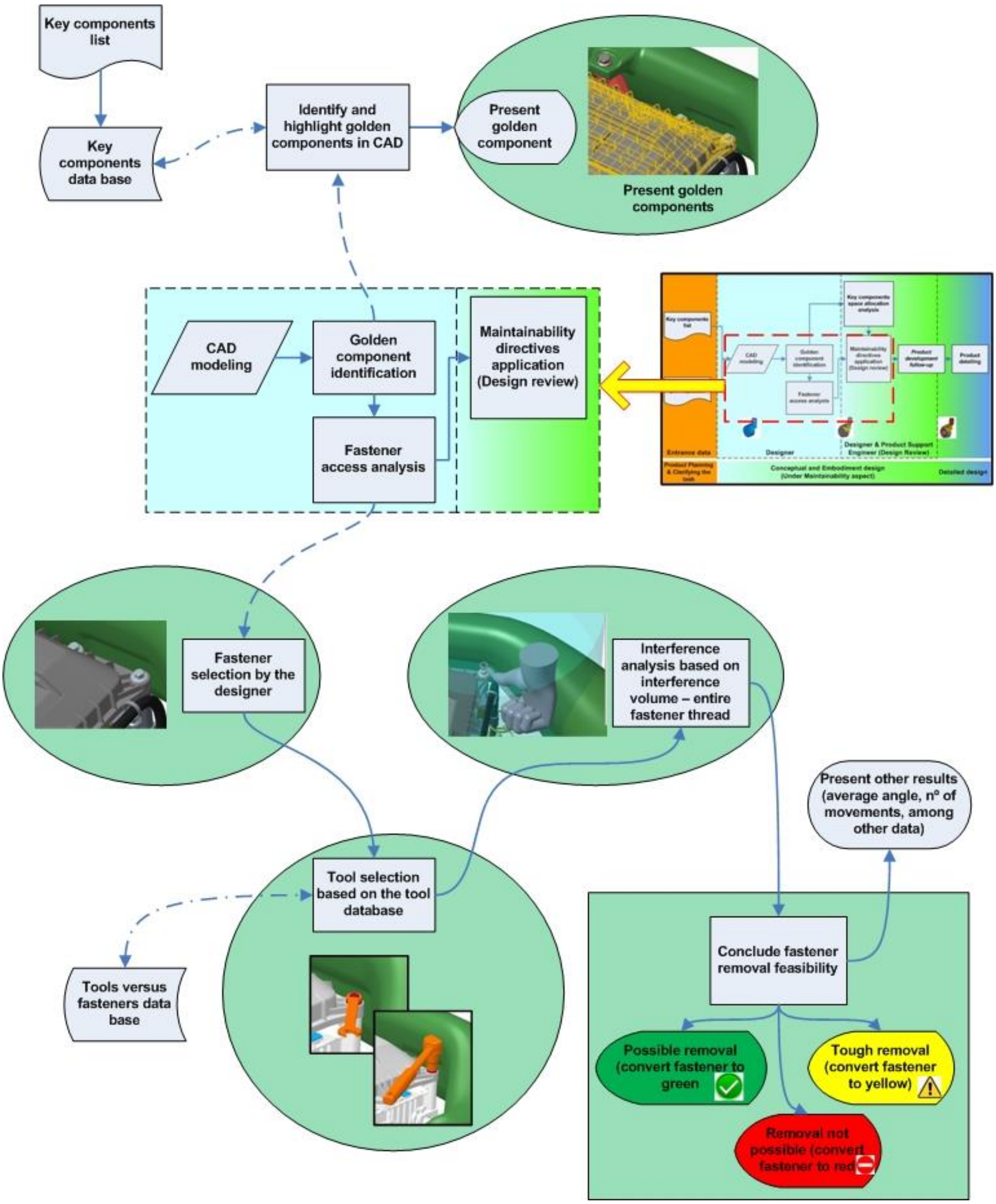


Figure 3.6 – Maintainability model

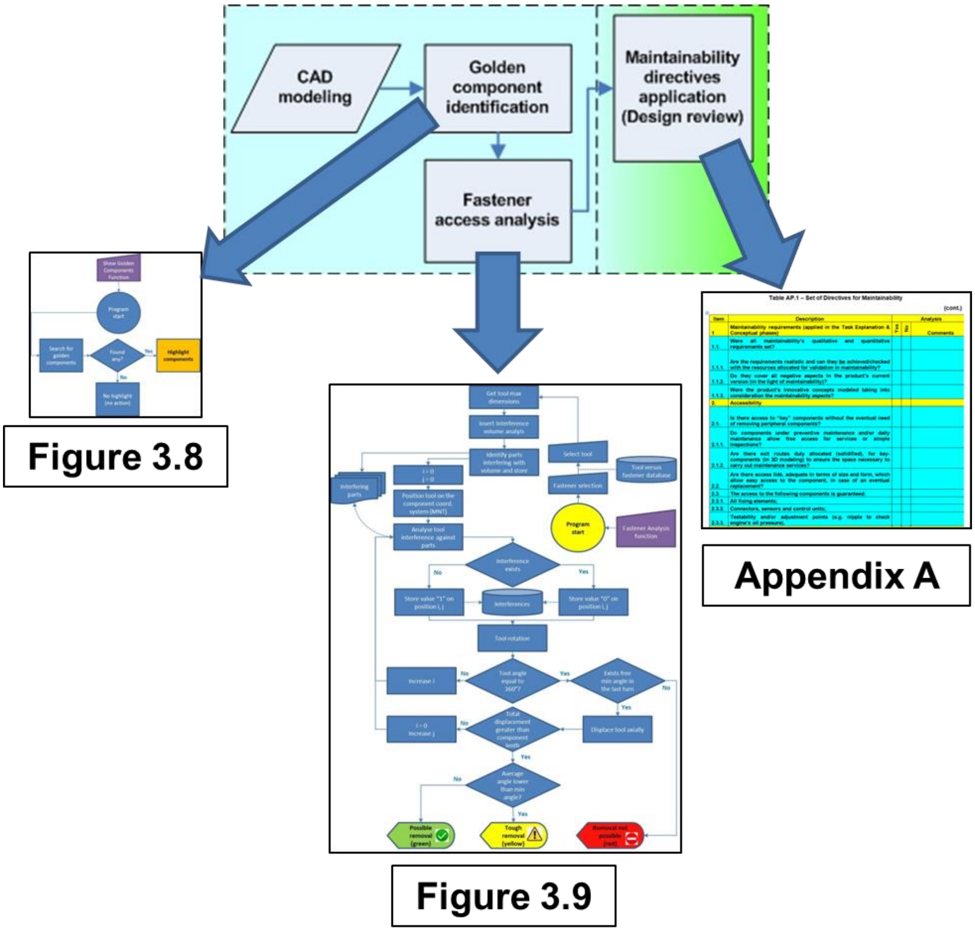


Figure 3.7 – Maintainability model details

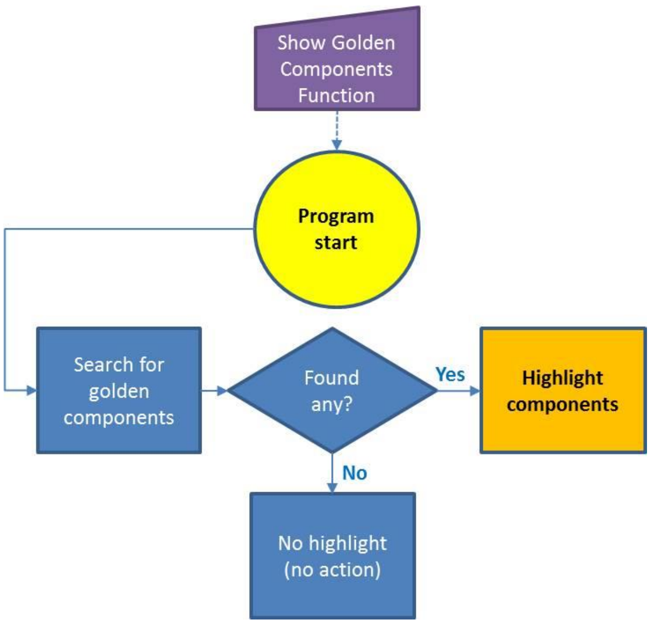


Figure 3.8 – Show golden components function

3.2.1.1. Golden componente identification pseudocode

A pseudocode for the Golden component identification is presented below:

FOR each Part in Global_assembly

IF Part.name is in Golden_components_list THEN

HIGHLIGHT Part

END IF

END FOR

3.2.2 Fastener analysis

Then, to develop the model and associated tool (plug-in) to enhance accessibility analysis by automating reachability and the space required to maintain a product by focusing on fasteners would demand some specific steps, as presented on Figure 3.9.

Basically, Figure 3.9 brings the following flow for the fastener analysis:

a. The plug-in starts with fasteners selection by the designer;

b. In the plug-in three simple options of tools are available (regular wrench, star spanner or ratcheting wrench). The idea is not to populate the tool database with several different tools, but only to present the concept of automating fastener reachability and space required to remove it;

c. Plug-in performs a complete screw thread analysis. At each screw thread turn the tool verifies whether there is clash or not:

c.1. IF it is feasible to remove fastener with an average removing angle greater than the minimum angle (refer to 3.1.1.1), plug-in converts the selected fastener to a green colour – stating that this fastener has a good accessibility;

c.2. IF it is feasible to remove fastener but with an average removing angle lower than the minimum angle (refer to 3.1.1.1), plug-in converts the selected fastener to a yellow colour – stating that this fastener has a minimum accessibility level that may be improved;

c.3. IF it is not feasible to remove fastener, then plug-in converts the selected fastener to a red colour – stating that is not possible to remove fastener in the current CAD model scenario.

Further details on the plug-in usage are found on section 3.5.

3.2.2.1. Fastener analysis complete description

This section describes the plug-in functionality core part – fastener analysis, related to Figure 3.9 framework. Basically, the whole maintainability fastener analysis starts when the user press the button "Select Fastener" (Figure 3.42).

The first steps, after the actual fastener and tool selection from a cross database, are related to the interference volume analysis.

To rapidly identify the parts that might interfere in the set removal (tool and hand), the interference volume is created and positioned in the CAD module.

3.2.2.1.1 Interference volume dimension

The first action is to identify the box volume aligned with the coordinate system (Figure 3.10). Mandatorily the tool model must hold the fastener removal axis aligned with the global Y axis. The tool top surface has to be aligned as well with the fastener top edge. With this volume identified, dimensions ∆x1, ∆x2, ∆y1, ∆y2, ∆z1 and ∆z2 are obtained by comparing the external dimensions of the volume with the position of the tool coordinate system (CSYS MNT). Note: Figure 3.10 brings the analysis of a tool only, but by analogy the same representation is valid if a virtual hand is included (hand and tool are considered then as a joint tool set).

The dimensions ∆x1, ∆x2, ∆z1 and ∆z2 determine the interference volume radius following the equation (Pythagoras Theorem):

$$R = (Max(\Delta x1, \Delta x2)^2 + \; Max\;(\Delta z1, \Delta z2)^2)^2 \qquad (1)$$

As the coordinate system is not always positioned in a way to coincide the tool edge with the volume boundary, a residue ∆r (dr) is generated and increases the volume in some distance in order to cover the entire tool.

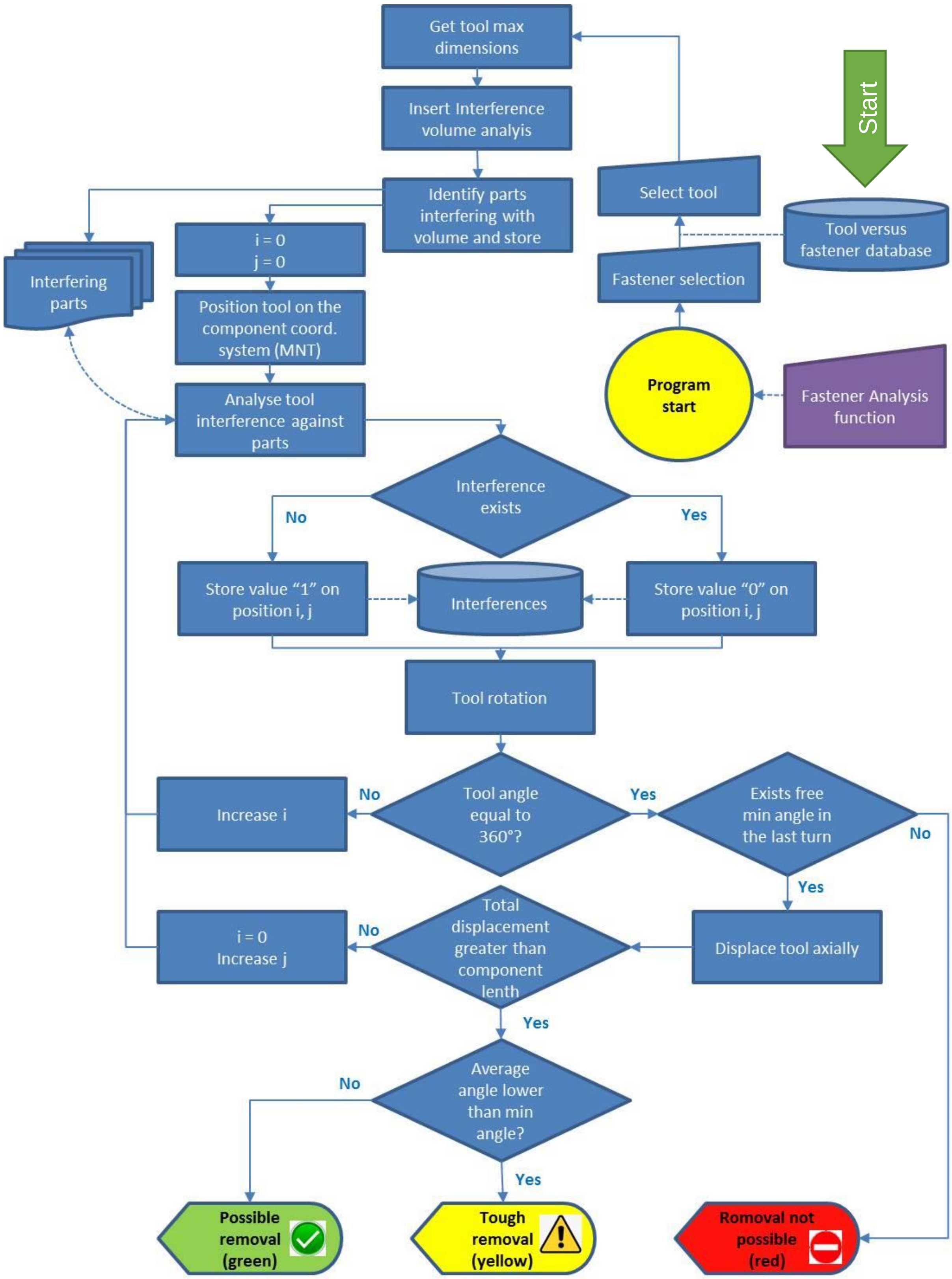


Figure 3.9 – Fastener analysis function

Dimensions ∆y1 and ∆y2 and the fastener total length set the height of the interference volume. The interference volume that stays under the plan XZ is determined by the following equation:

$$Y1 = \Delta y2 + 1\ \mathrm{mm} \quad (2)$$

The addition of 1 mm on the equation above is necessary for program stability, once if dimension ∆y2 is equal to zero (in case the coordinate system is positioned on the lower tool surface) the plug-in presents an error (inaccurate results are presented).

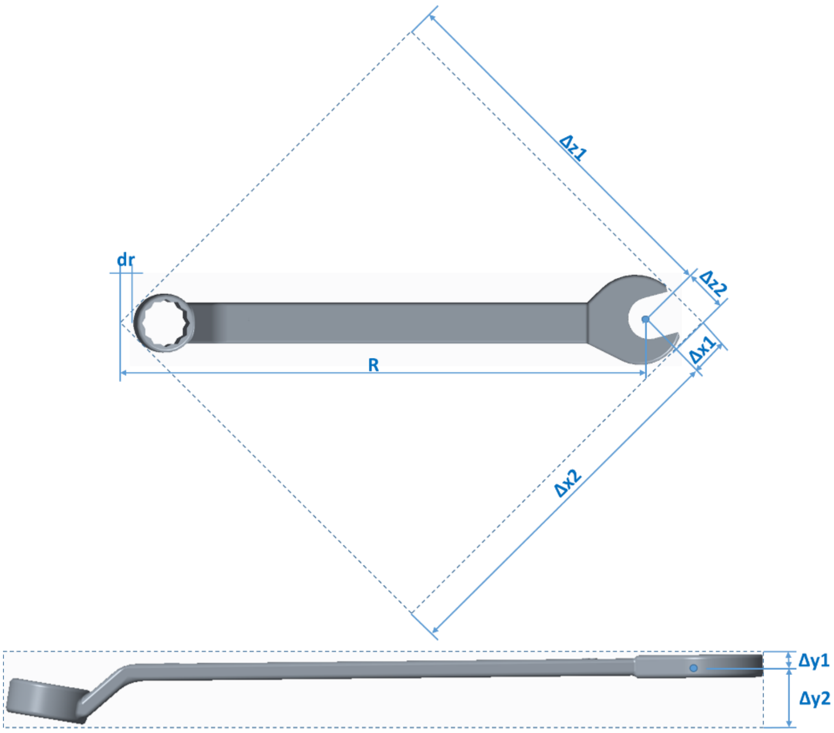


Figure 3.10 – Tool connection with coordinate system

The dimension of the interference volume above XZ is defined by the following equation:

$$Y2 = \Delta y1 + \text{fastener total length} \quad (3)$$

Therefore:

$$Interference\ volume\ height =\ \mathrm{Y1} + \mathrm{Y2} \tag{4}$$

The descriptions above assure that the volume trekked by the tool during its revolution and translation on the y axis stays within the interference volume defined. Additionaly, the safety multiplier (see 3.5.2.3) is multiplied by the values R, Y1 and Y2 to obtain the new interference volume dimensions.

3.2.2.1.2 Identification of parts interfering with created volume

The new generated interference volume is positioned in the CAD module aligned with the fastener CSYS MNT. Therefore, it clashes with other possible components in the assembly that might interfere with the tool movement along the removal simulation.

A search is performed with all ".prt" components verifying possible clashes with the interference volume. In case an interference is found, the component code is inserted in a vector V_components.

3.2.2.1.3 Movement and evaluation

With the information of which components will interfere with the tool, the actual tool is positioned in the fastener coordinate system origin (CSYS MNT). The plug-in verifies if the tool interferes with any of the components included in V_components. If an interference is found value "0" is stored in the matrix I_{mxn} (interference matrix), otherwise "1". The index **n** refers to the angle step that the tool turns, and the index **m** refers to the axial movement on the y axis.

$$Interferências_{m\,x\,n} = \begin{bmatrix} I_{00} & I_{01} & \cdots & I_{0n} \\ I_{10} & I_{11} & \cdots & I_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ I_{m0} & I_{m1} & \dots & I_{mn} \end{bmatrix}$$

Next, the tool is rotated a Δ angle (configured in the plug-in by the user) around the Y tool axis. Index n is increased and a new interference evaluation is performed with components in V_components.

When reaching 360° after successive rotations of Δ angle, is performed an evaluation of the maximum angle in this rotational movement.

An example is given in order to illustrate how the maximum angle is calculated. Considering a ∆ angle of 20º and one arbitrary line y from the interference matrix:

Interference$_y$ = [**1 1** 0 0 0 0 0 0 0 **1 1 1 1** 0 0 **1 1 1**]

In this set of rotations is possible to identify three groups in which no interference is found, starting on positions 0, 9 and 15. Suming two, four and three non-interferent positions (40º, 80º and 60º). However, the first and the third groups are located at the very start and the very end of the vector therefore forming a unique group (due to the rotational movement). Therefore, in this movement vector there are two groups of movements, one with 80° and another with 100º.

With the maximum angle collected from this cycle, a comparison is performed with the maximum angle configured (see section 3.5.2.2). The lowest value is captured (lowest_maximum angle). From this result, the y displacement is obtained by the following formula:

$$y\ displacement = fastener\ pitch * \left(\frac{Lowest\ maximum\ angle}{360°}\right) \tag{5}$$

Next step, the tool is moved axially towards tool Y+ axis with a distance equal to "y displacement", and the total displacement is also increased by "y displacement".

If value of "y displacement" is equal to zero, plug-in returns the information that it is not feasible to remove the fastener, otherwise index **n** is reset (set to 0), **m** is incremented and a new rotational sequence and evaluations from the plug-in is started.

When the total displacement is equal or greater than the entire fastener length, plug-in returns that is feasible to remove the fastener. In this case:

a. IF the average angle (calculated from the entire simulation) is lower than the minimum angle (see 3.1.1.1), system returns that fastener is possible to be removed but with poor accessibility level;

b. IF the average angle (calculated from the entire simulation) is greater than the minimum angle (see 3.1.1.1), system returns that fastener is possible to be removed with good accessibility level.

3.2.2.2. Fastener analysis pseudocode

A pseudocode is presented below to support Figure 3.9 explanation:

Insert_Part(Tool, Csys_MNT)

Interference_volume = Create_interference_volume(Tool, Csys_MNT)

FOR each Part in Global_assembly

IF Interference between Interference_volume and Part is equal to TRUE THEN

ADD Part to V_components

END IF

END FOR

SET i TO 0;

WHILE Y_displacement < Fastener_length

FOR j equal to 0 TO 360/Delta_angle - 1

SET Interferences[i][j] TO 0

FOR each Part in V_components

IF Interference between Part and Tool is equal to TRUE THEN

SET Interferences[i][j] TO 1

BREAK

END IF

END FOR

IF Interferences[i][j] is equal to 0 and SHOW_MOVEMENTS is equal to TRUE THEN

Refresh_tool_position()

END IF

Rotate_tool(Tool,Delta_angle)

END FOR

SET Maximum_rotation[i] TO Lowest_maximum_angle(Interferences[i])

IF Maximum_rotation[i] < Minimum_removable_angle THEN

Can't_remove_part()

BREAK

END IF

*SET Delta_l TO Maximum_rotation[i] * Passo_fastener*

Move_tool_axialy(Csys_fastener, Tool, Delta_l)

INCREMENT Y_displacement by Delta_l

INCREMENT i by 1}

3.3 Maintainability directives application

After verifying the golden components and their fastener' access level, the model intends to propose the usage of the directives presented on Appendix A. They should be used as a guide, supporting CAD specialist to think about product maintenance while the product concept is being developed. This would minimize the level of reworks supressing slightly the need of people with a very specific expertise (field maintenance experience and CAD know-how).

3.4 Evaluation of fasteners removal barriers

Before entering in a deeper plug-in usage and explanation section, it is important to understand what kind of fastener removal barriers the plug-in has to deal with.

In this section, a close evaluation of fastener removal barriers is presented. The idea is to study the step by step that is involved in a fastener removal in order to understand its possible removal obstacles. These identified barriers will serve as test-case for the plug-in explanation as well as the foundation for the verification and validation chapter in which the fastener accessibility model (Figure 3.7) will be tested against.

3.4.1 Base set

Junior (2015) proposed a simple base set to explore his study (presented on Figure 3.11). Basically it holds a M10 hex screw 20 mm long (based on DIN 6921 standard).

In order to simulate the removal of the screw Junior also presented some different tools. Two of them are shown on Figure 3.12 and Figure 3.13. On Figure 3.12 there are two sides, one is a regular wrench (Figure 3.12 **B**) and another is the star spanner (Figure 3.12 **A**). Figure 3.13 is a ratcheting wrench. Positive side of using a ratcheting wrench (Figure 3.13) is that mechanics gain time compared to a regular wrench. In the other hand a simple wrench occupies less space compared to a ratcheting wrench.

Note: the hex screw and tools presented will be further explored in this thesis analysis.

When observing a screw being removed from its position, as it only has one direction to be extracted, it is simple to determine its exit route. The removal path though will be very dependable on the fastener head type and the defined tool.

A regular screw driver has it access point from the top (Figure 3.14 **a**), while a wrench normally demands a perpendicular tool access for the mechanic hand in order to be removed (Figure 3.14 **b**).

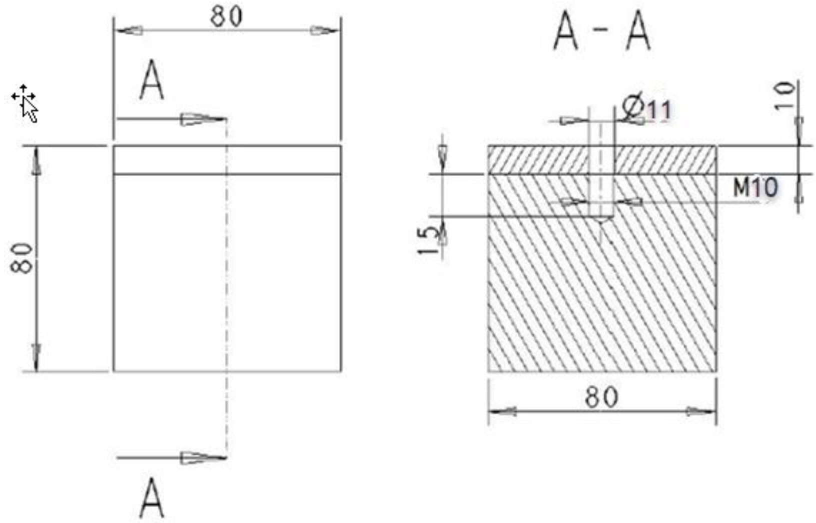


Figure 3.11 – Base set (mm) model
Source: Adapted from Junior (2015).

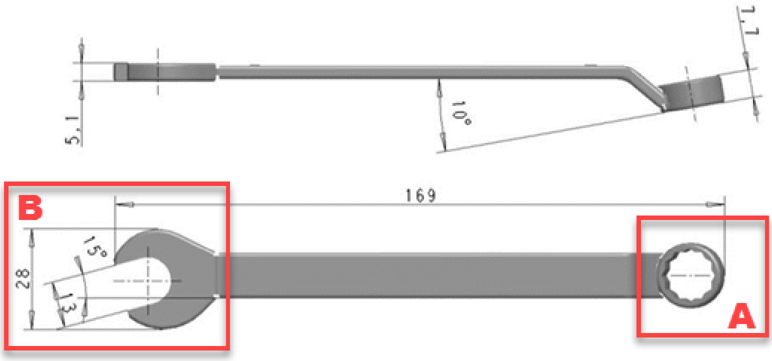


Figure 3.12 – Combined wrench (mm)
Source: Adapted from Junior (2015).

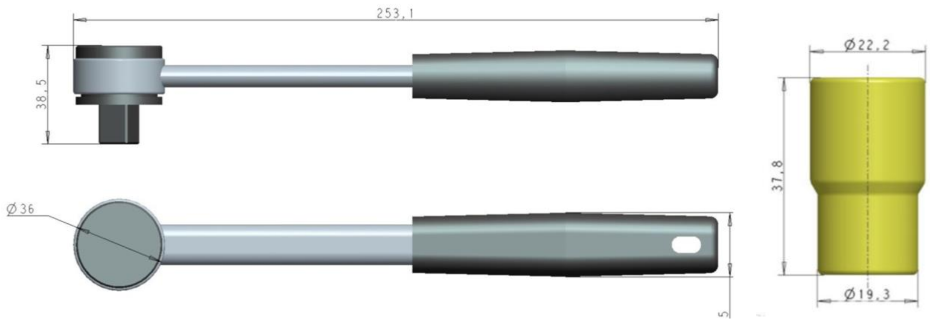
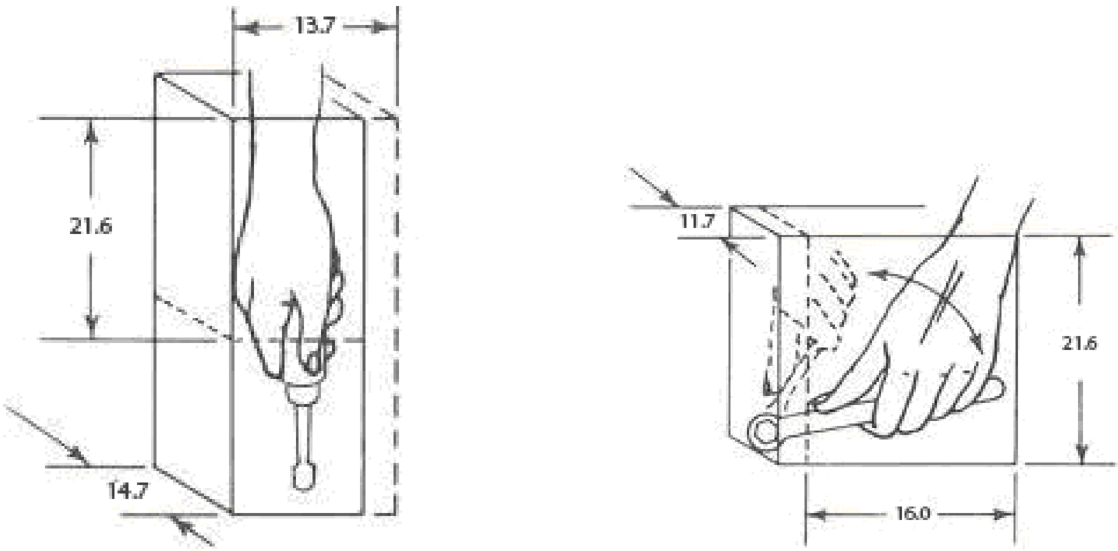


Figure 3.13 – Ratcheting wrench with socket for M10 Screw hex head (mm)
Source: Adapted from Junior (2015).



a/ Screw driver access b/ Wrench access

Figure 3.14 – Type of tool access
Source: Adapted from Blanchard, Verma and Peterson (1995).

By evaluating the base set from Junior (2015) on Figure 3.15 it is possible to conclude that either using a wrench or a ratcheting wrench with a socket, the screw will be removed with no clashing. As there is a 360º angle available, in this scenario a mechanic can freely chose the tool to be used and also the angle of actuation.

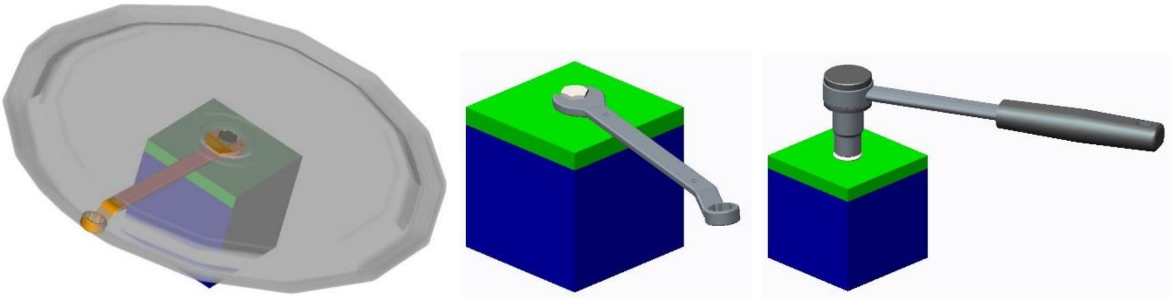


Figure 3.15 – Full space available for fastener removal

3.4.2 Angle constraint barrier

Figure 3.16 shows the base set slightly modified in order to represent a removal angle constraint. Now, it is no longer possible to actuate on a 360º (even though there is freedom enough to remove the screw). It means that a mechanic, by performing several hand twisting motions with a selected tool with a limited angle, may remove the fastener from its starting position until the complete screw's thread is removed.

An even more limiting lateral barrier may also limit a hand twisting motions during a fastener removal as shown on Figure 3.17.

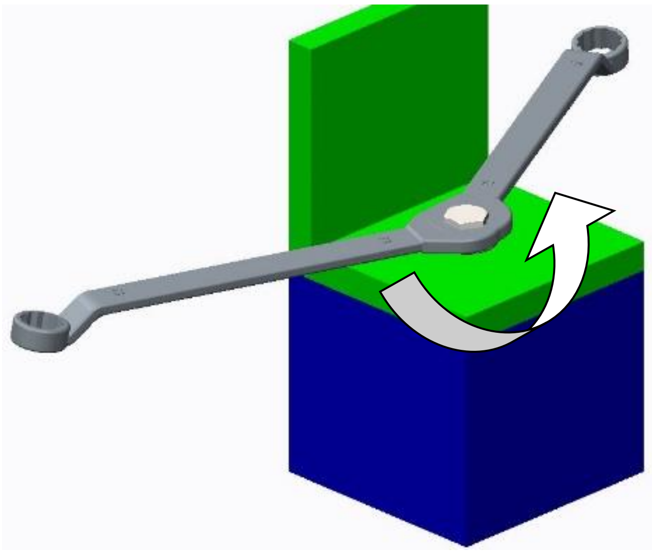
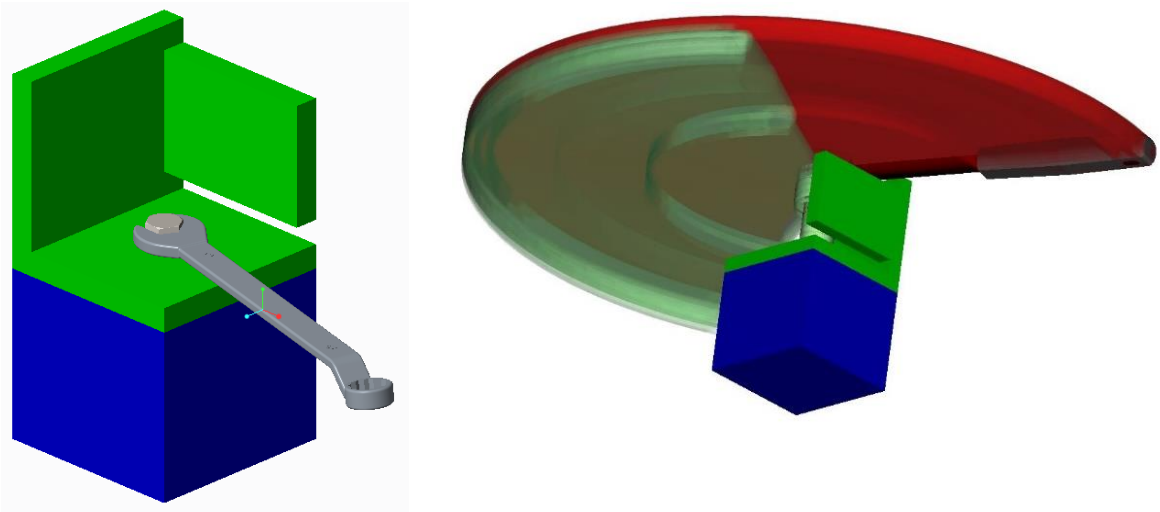


Figure 3.16 – Fastener removal with angle constraint



a/ Limiting lateral barrier b/ Limiting lateral barrier movement simulation

Figure 3.17 – Fastener removal with further angle constraints

Figure 3.18 shows a real example in which a mechanic has a limited angle of actuation.

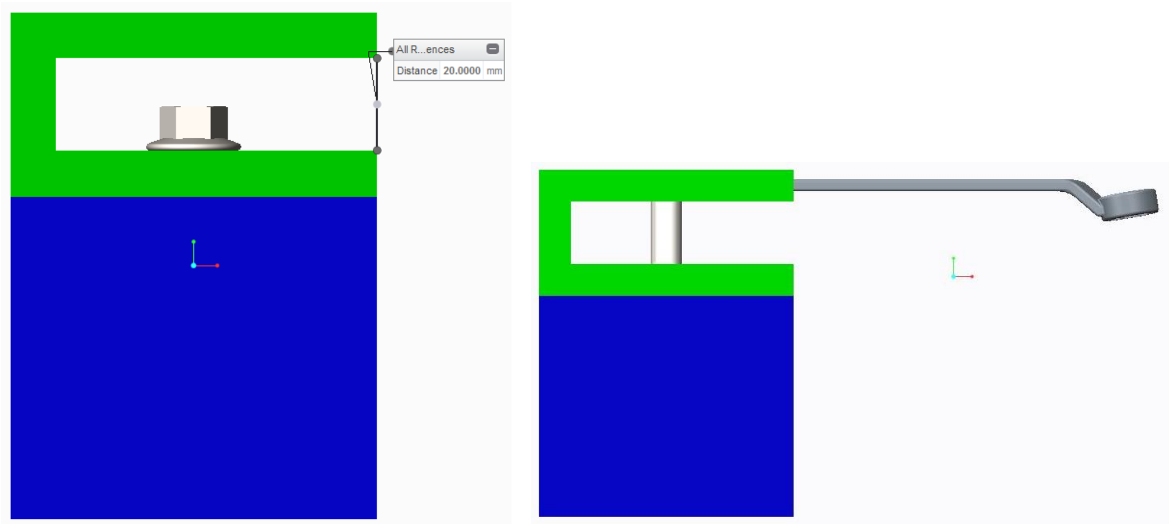
a/ Wrench access b/ Star spanner access

Figure 3.18 – Type of tool access – angle constraints examples

3.4.3 Top barrier

Another barrier that may be presented is a top blockage on the direction of a fastener removal. If the fastener length is bigger than the distance between its initial and final position during the removal procedure, then of course it will be impossible to remove it, unless the obstacle is firstly removed. Virtual examples of such barrier were already offered on Figure 2.49 and Figure 2.50.

Figure 3.19 shows a top blockage of 20 mm. Considering that the total length of the screw is 29.7 mm it is obvious that it is impossible to remove the screw.



a/ Top blockage of 20 mm

b/ Screw on its removed position showing a clash

Figure 3.19 – Limited angle of actuation and top blockage (20 mm) for a fastener removal

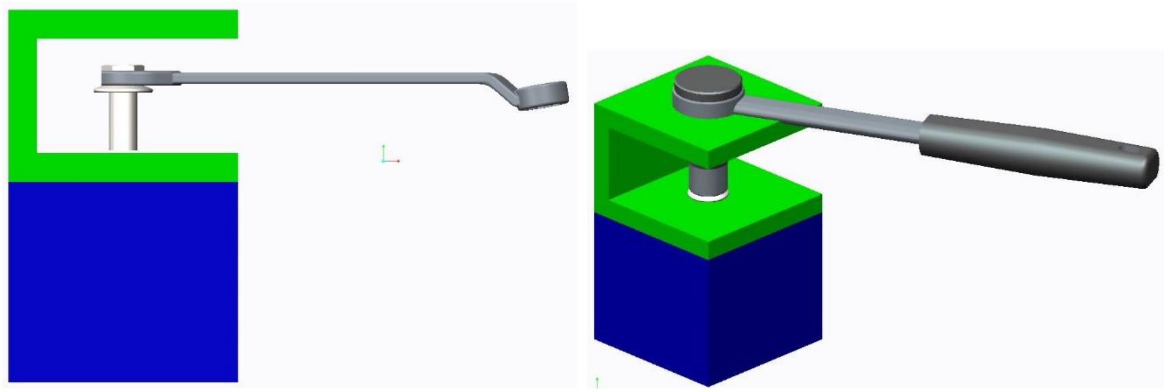
Figure 3.20 presents a top blockage of 40 mm. In this scenario it is feasible to remove the fastener with a regular wrench, but it is not possible to remove it with a ratcheting wrench with socket.

Figure 3.21 brings a top blockage of 90 mm. In this context, either with a ratcheting or regular wrench it is feasible to remove the fastener.

A real life example of top blockage is presented on Figure 3.22.

On the plug-in concept there is one top blockage that is not possible to evaluate. If there is a blockage on the top of the fastener only, the plug-in will not be able to catch such barrier as the fastener removal itself is not considered in the analysis (see Figure 3.23). Further explanation is given on section 3.5.1.2.1.

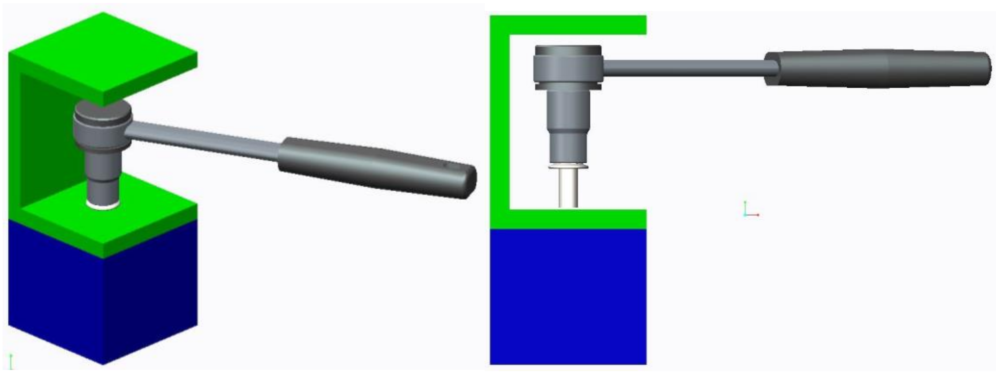
A summary table was created showing the barrier examples. Validation models presented on Table 3.2 and on the earlier figures will serve in the next section to validate the plug-in developed in this research. Further details are provided in the corresponding verification and validation section.



a/ Top blockage of 40 mm

b/ Not possible to remove screw with a ratcheting wrench

Figure 3.20 – Limited angle of actuation and top blockage (40 mm) for a fastener removal



a/ Top blockage of 90 mm

b/ Possible to remove screw with a ratcheting wrench

Figure 3.21 – Limited angle of actuation and top blockage (90 mm) for a fastener removal

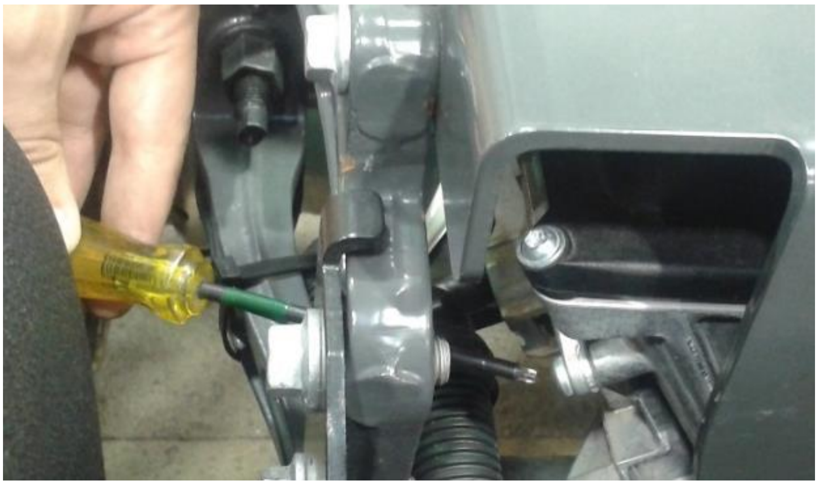


Figure 3.22 – Real example of screw removal top blockage

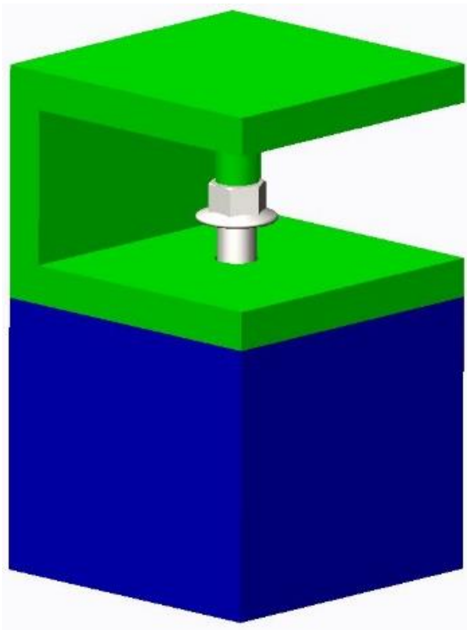


Figure 3.23 – Example of top blockage not possible to be evaluated by the plug-in

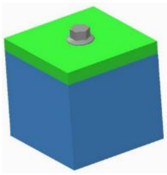
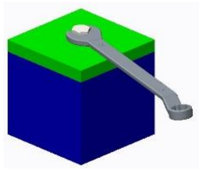
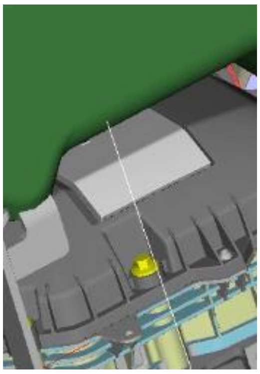
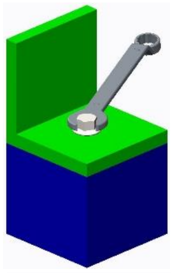
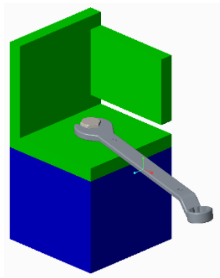
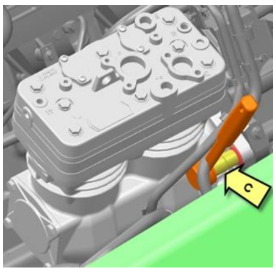
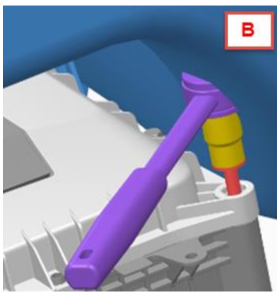
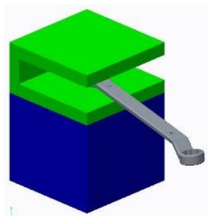
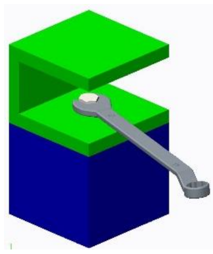
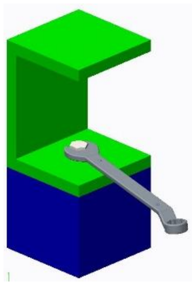
3.4.4 Illustrative barrier example from the literature

Furthermore on Chapter 4, some extra plug-in validations will be performed in order to verify the solution provided by the plug-in. Two extra examples are given, one from Popescu and Iacob (2013) and another from Junior (2015).

Popescu and Iacob (2013) presented in their study one drawing example to support their research on a disassembly method based on connection interface and mobility operator concepts. They propose an illustrative example in which letter "**C**" denotes components and "**F**" denotes fasteners (see Figure 3.24 and Figure 3.25).

They have used it to propose an optimal disassembly sequence as shown on Figure 3.26. It is possible to observe in such sequence that is only feasible to remove **F1** if **C2** is removed in advance. Comparing this removal barrier issue against Table 3.2, a "Top barrier" is found. In the next chapter, this example from Popescu and Iacob (2013) which was converted into a 3D model is used to validate **F1**, **F2** and **F3** fasteners access (see Figure 3.27 with different 3D views).

Table 3.2 – Summary of fastener removal barriers

Type of barrier	Models examples	Real examples	Validation models
Free angle of actuation			
Angle constraint			 
Top barrier	 		  

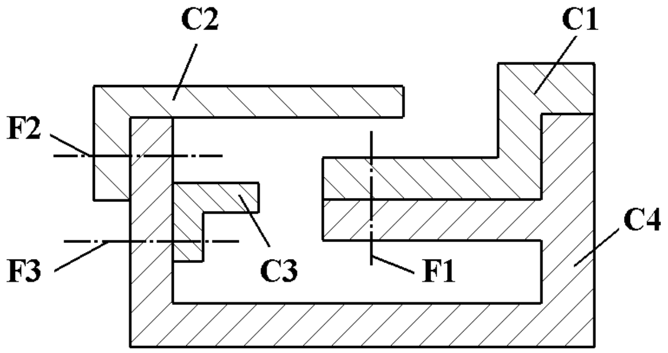


Figure 3.24 – Illustrative example from disassembly method
Source: Popescu and Iacob (2013).

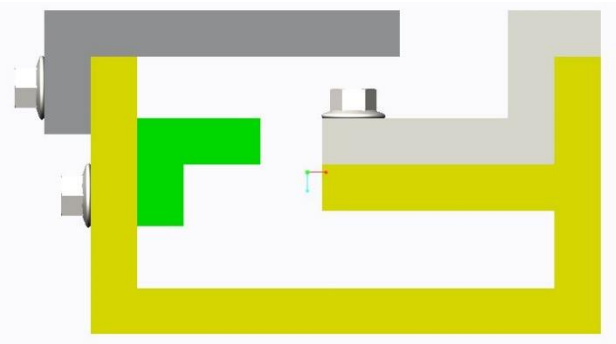


Figure 3.25 – Illustration based on Popescu and Iacob study

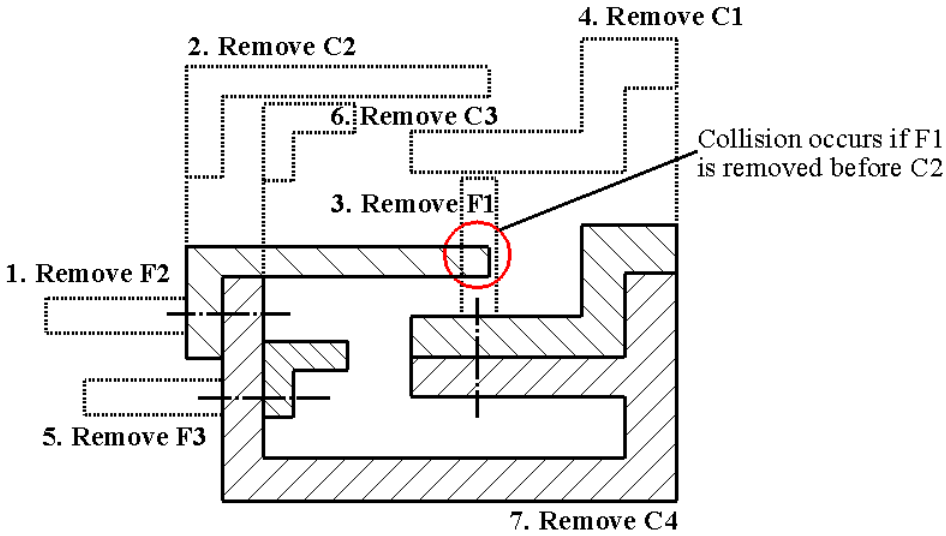


Figure 3.26 – Removal steps for the illustrative example
Source: Popescu and Iacob (2013).

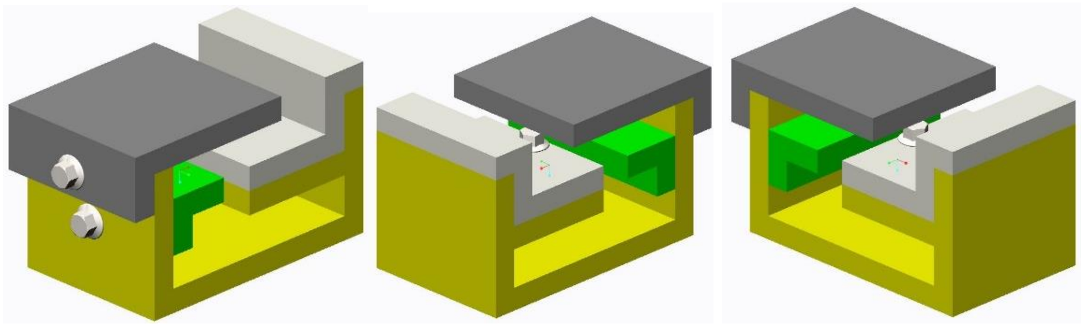


Figure 3.27 – 3D model based on Popescu and Iacob example (from different views)

3.4.5 Verification model (barrier) from another plug-in concept

Junior (2015) compared a manual work and an improved maintainability evaluation through a plug-in developed (example given on Figure 3.28). Basically, this approach proposes the usage of standard swept volumes (which includes a hand, tool, socket and the actual fastener) during its removal path using a pre-selected tool twisting movement (15º, 30º, 45º and 60º).

Junior (2015) compared a manual work using a CAD system against its plug-in concept using as a reference the model presented on Figure 3.29.

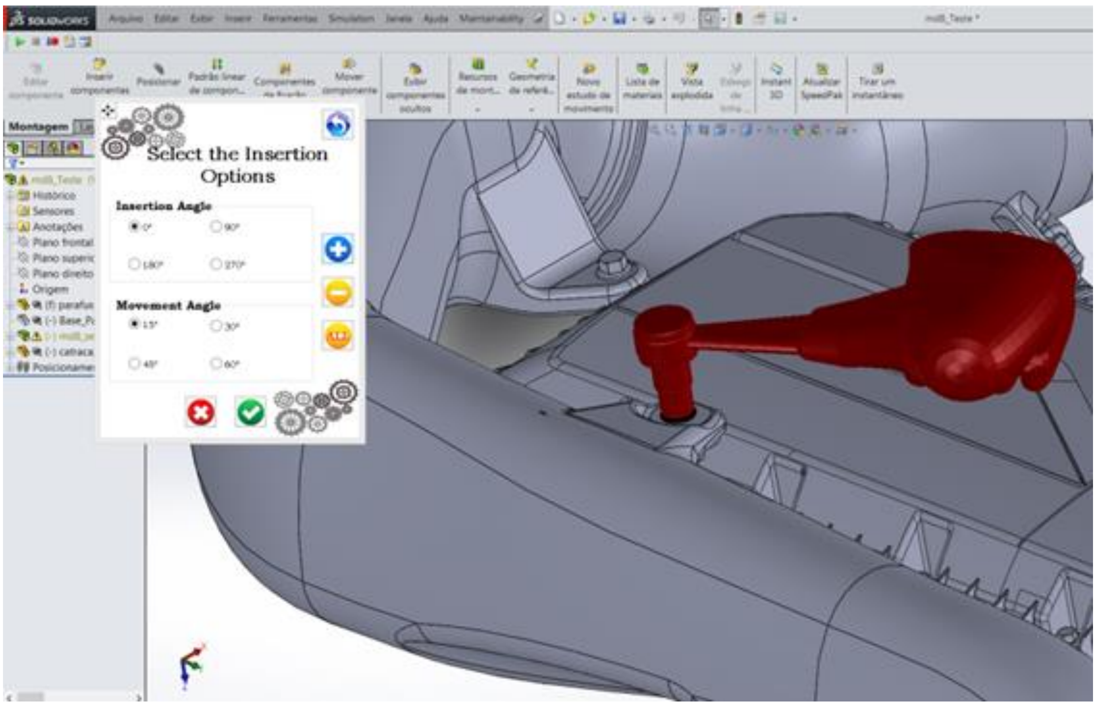


Figure 3.28 – Swept volume plug-in concept
Source: Junior (2015).

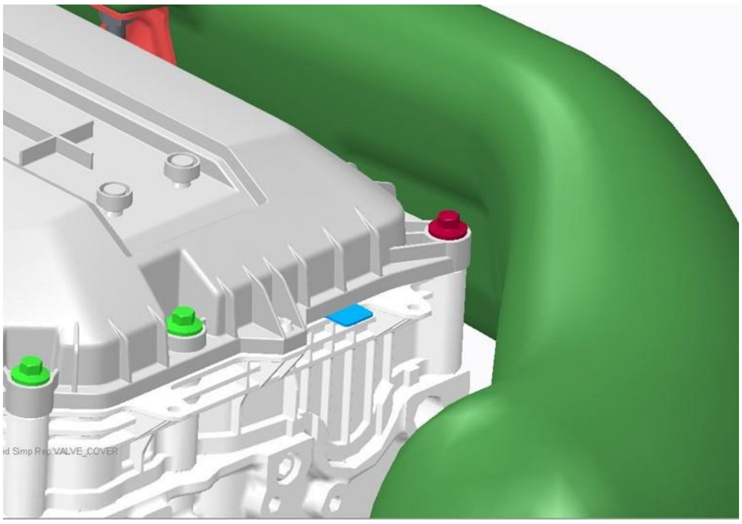
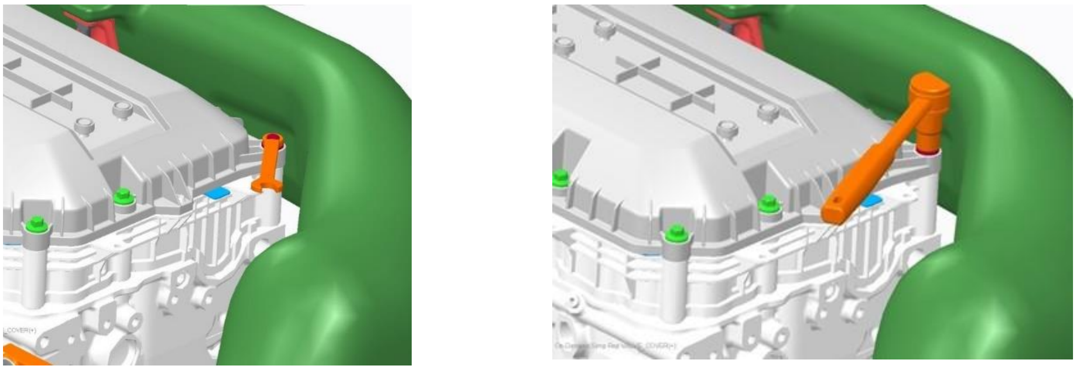


Figure 3.29 – Verification model used as case study for swept volume plug-in concept
Source: Junior (2015).

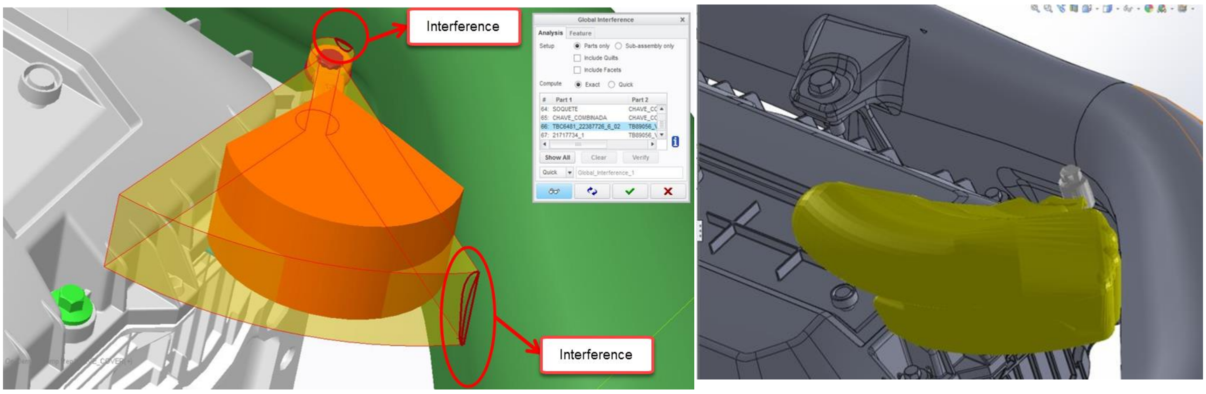
In this reference model, one interesting output is the fact that only a regular wrench can be used (examples given Table 3.2). If a star spanner (Figure 3.30 **a** and Figure 3.31 **a**) or a ratcheting wrench (Figure 3.30 **b**) are used the conclusion is that there is no space for the removal. This is an interesting fact to be verified and validated in Chapter 4 as well with the new plug-in proposed by this thesis research.



a/ star spanner b/ ratcheting wrench

Figure 3.30 – Verification model tools visual analysis
Source: Junior (2015).

Junior (2015) produced a time comparison between the manual work using a CAD system against his plug-in concept. On a manual analysis the researcher took 55 minutes to perform a complete evaluation (Figure 3.31 **a**), as with his plug-in the analysis time was reduced to 14 minutes only (Figure 3.31 **b**). On chapter 4, a time comparison is another verification and validation step of the new plug-in proposed by this thesis in order to present time analysis enhancements.



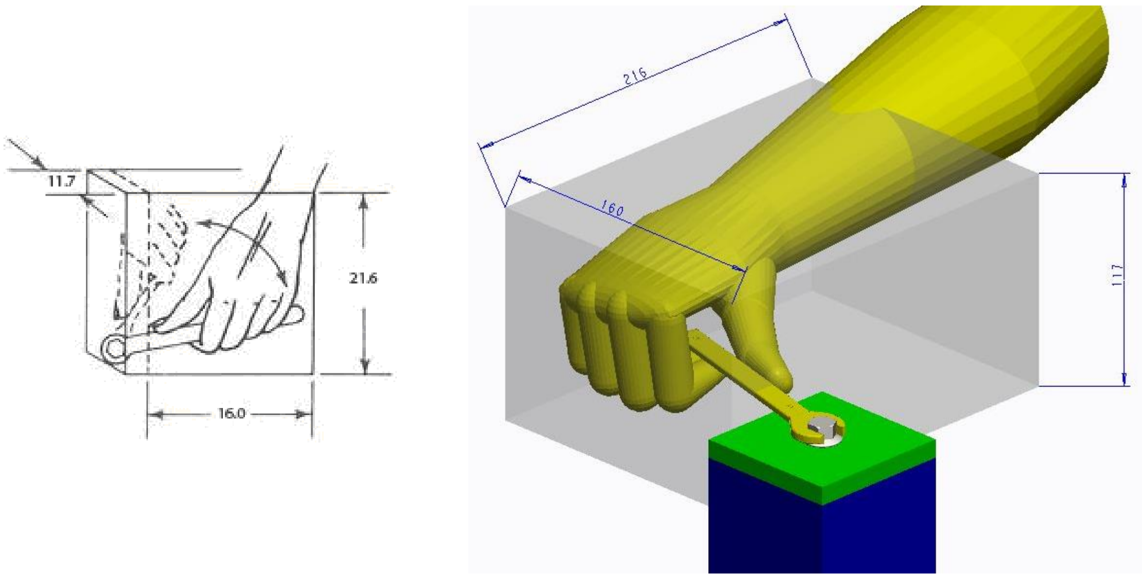
a/ manual evaluation b/ Junior (2015) plug-in analysis

Figure 3.31 – Manual versus plug-in analysis
Source: Adapted from Junior (2015).

3.4.6 Ergonomics involved

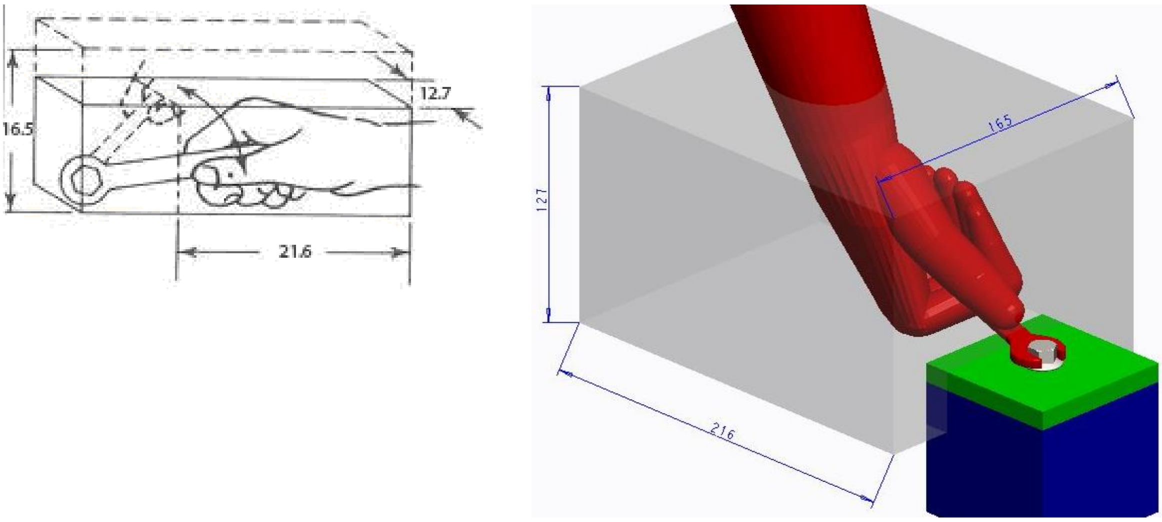
To be comparable with Junior (2015) research, a P95 hand is used as a reference in the analysis.

Figure 3.32 and Figure 3.33 present a comparison between a maintenance space required proposal from available literature versus P95 hand used by Junior (2015). The conclusion is that using such virtual hand is in accordance with literature therefore being feasible to perform such verification and validations with P95 hand size.



a/ Maintenance space – literature (cm) b/ P95 virtual hand comparison (mm)

Figure 3.32 – Comparison of hand size against available maintainability literature – side position
Source: Adapted from Blanchard, Verma and Peterson (1995).



a/ Maintenance space – literature (cm) b/ P95 virtual hand comparison (mm)

Figure 3.33 – Comparison of hand size against available maintainability literature – top position

Source: Adapted from Blanchard, Verma and Peterson (1995).

3.5 Plug-in usage and explanation

To start with, one important topic was to select a CAD platform in order to decide in which system the maintainability model should be framed. The decision points were:

a) Programming language: C language. The reason for choosing such programming language was directly connected to the CAD system decision;

b) PTC Creo was selected as the CAD system. Main reasons for this selection are: i) earlier plug-in developed by Moscheto (2009) was already built using an earlier version of this software; ii) Future possibility of using maintainability enhancements from this work all together with IMMA (ergonomic analysis) and IPS (path-planning analysis) as Fraunhofer-Chalmers Centre (IMMA/IPS developers) are connecting their software platforms to PTC Creo; iii) System openness: as bill of material, parts relations matrix, path planning features, system library, system features/tools availability, among others, are all in-built with the CAD systems. Therefore, base software needed to be defined with some degree of openness. PTC Creo has a Toolkit which enables users to interact with the CAD system – ideal for creating a plug-in (part of the study aim).

The tool that instantiates the proposed model, in the form of a plug-in was therefore programmed using C language with the libraries supplied by PTC Creo Parametric Toolkit (3.0 version).

The plug-in is available on PTC Creo Parametric as an extra tab in the software top menu. It is necessary to run “Auxiliary Applications” under “Tools” menu (Figure 3.34).

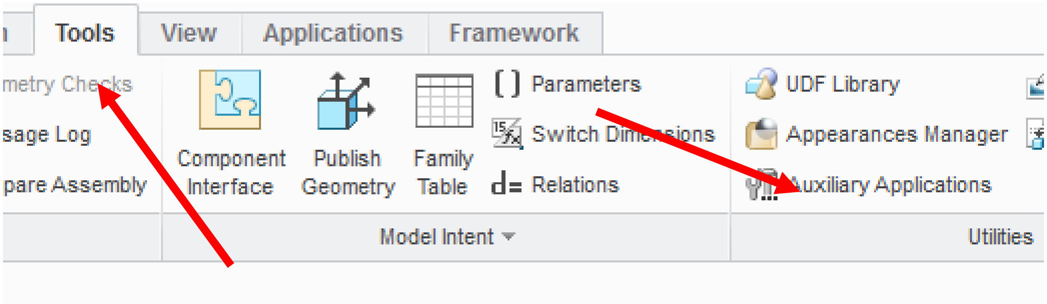


Figure 3.34 – Plug-in start-up in PTC Creo Parametric 3.0 – auxiliary applications

Then search for file “protk.dat” in folder “C:\mantenabilidade” by clicking on “Register” button (Figure 3.35).

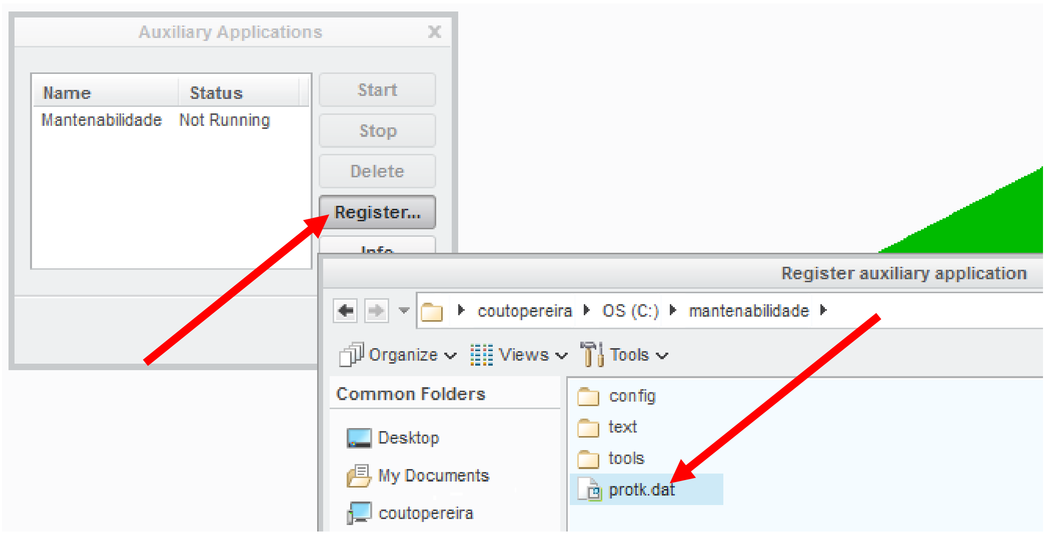


Figure 3.35 – Plug-in start-up in PTC Creo Parametric 3.0 – base file

Final step to start the plug-in is to select program “Mantenabilidade” and press “Start” button (Figure 3.36).

Tab “Maintainability” will appear in PTC Creo Parametric 3.0 (Figure 3.37). Two options are available: i/ Accessibility; and ii/ Configurations. On the next section, both plug-in options are explained.

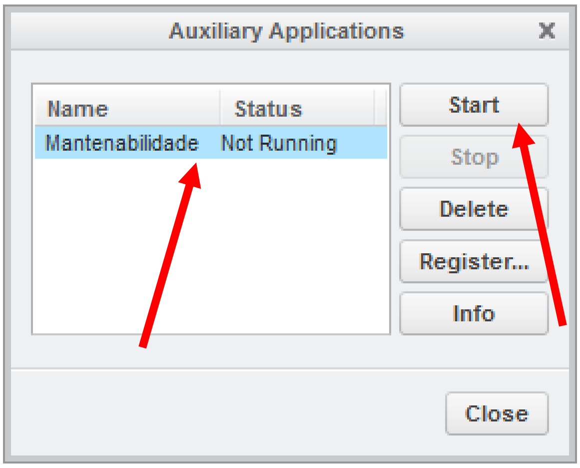


Figure 3.36 – Running the plug-in start-up in PTC Creo Parametric 3.0

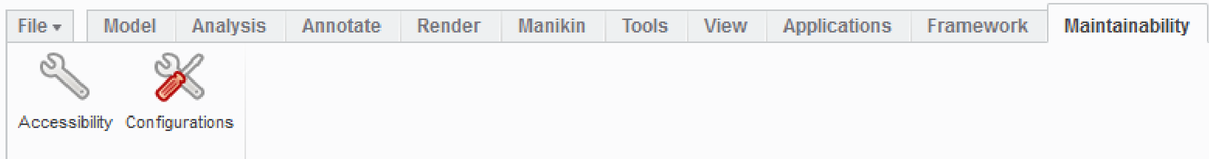


Figure 3.37 – Maintainability Plug-in Tab

3.5.1 Plug-in functionalities

The Accessibility window on Figure 3.38 is presented when button “Accessibility” is pressed (Figure 3.37). In this window the user is prompt with three different areas: i/ “Show Golden Components”; ii/ “Fastener analysis”; and iii/ “Results”.

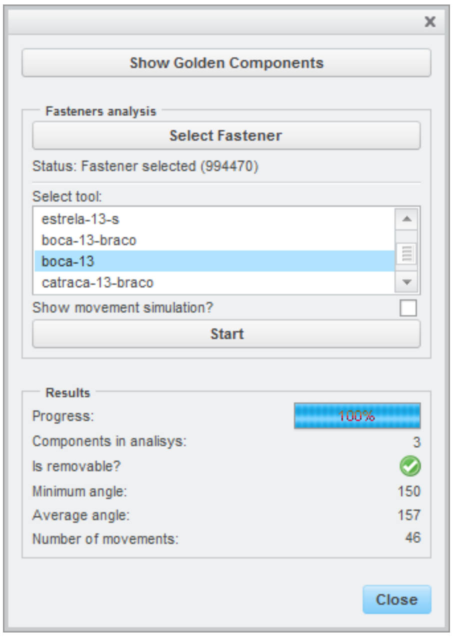


Figure 3.38 – Plug-in accessibility window

To create a connection between the plug-in and the maintainability model proposed by the thesis Figure 3.39 is offered.

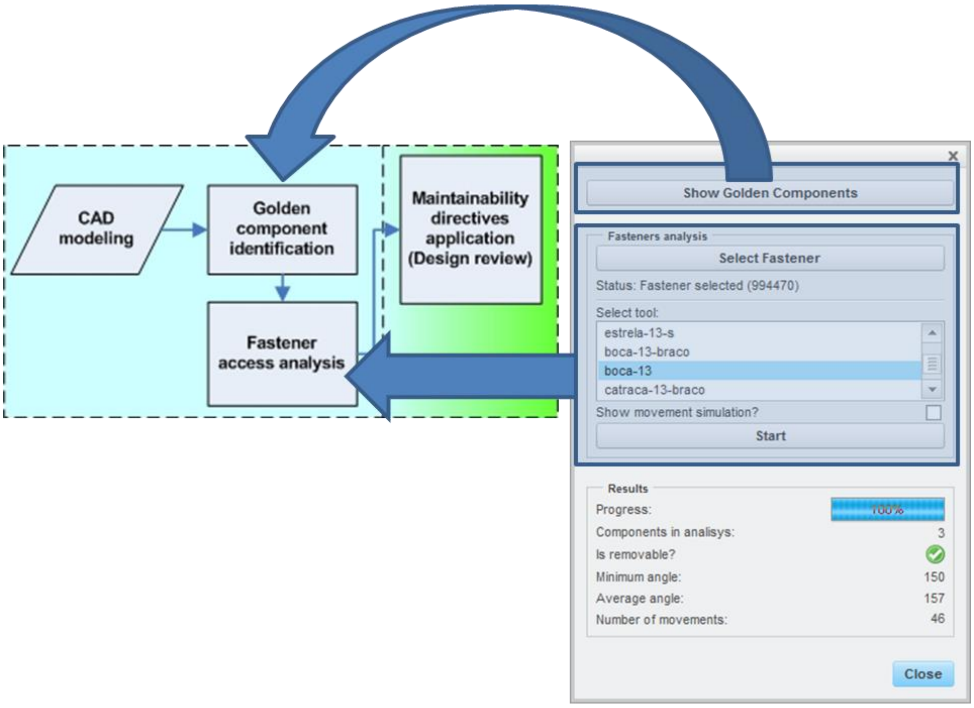


Figure 3.39 – Plug-in accessibility window

3.5.1.1. Show golden components functionality

By clicking on "**Show Golden Components**" button (see Figure 3.40) the plug-in seeks for components based on a parts' nomenclature list defined previously by the user. The list of parts may be composed by letters and/or numbers, which means from a pratical usage that parts' names and/or Part Numbers can be traced.

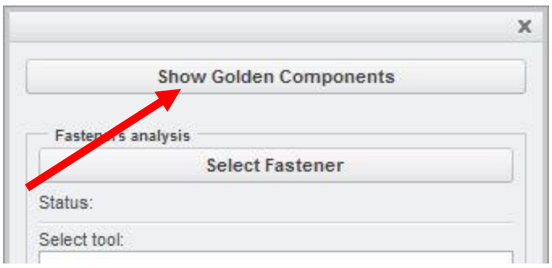


Figure 3.40 – Plug-in accessibility window – Golden components button

When such component is found, system highlights it just as presented on Figure 3.41. This functionality aims to help users to find/track most important components for the aftermarket in the assembly file. This idea is brought from Moscheto (2009) plug-in, but this time though the highlighted component it is not turned to a golden colour, only its edges are in fact highlighted (due to a different software solution offered by PTC Creo Parametric 3.0).

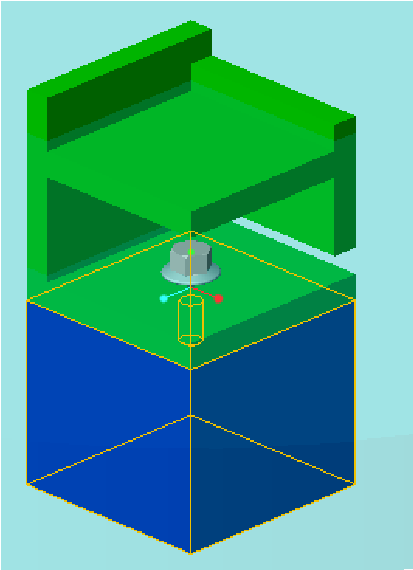


Figure 3.41 – Golden component highlighted

The aim with this functionality is to understand which components shall be prioritized and evaluated from a maintenance perspective.

3.5.1.2. Fastener analysis

With “**Show Golden Components**” function engineers find the most important components for the aftermarket. When such components are found, the user may select the second function of this plug-in: “**Fastener analysis**” (Figure 3.42). This function was developed to enhance accessibility analysis by automating reachability and the space required installing and removing fasteners.

Basically, the user presses the button “**Select Fastener**” and then selects a fastener from the CAD module (Fastener “**994470**” is selected on Figure 3.42). Then one of the possible tools available must be chosen (tool “boca-13-braco” is selected on Figure 3.43). Then, the user may either simulate the fastener removal by selecting “**Show movement simulation**” or not.

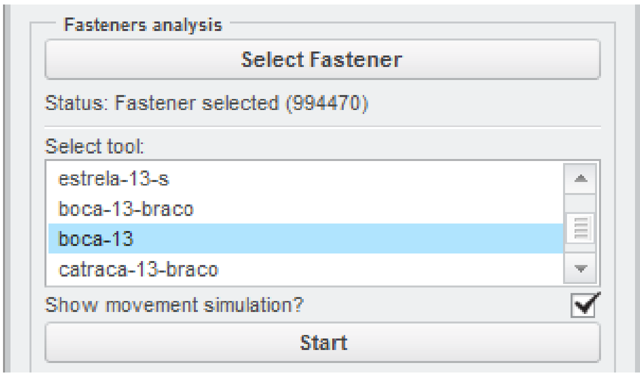


Figure 3.42 – Fastener analysis

Figure 3.43 shows one example in which the plug-in is simulating the removal of a screw with a regular wrench and a hand actually showing the entire movements simulation. Even though opting to present movement increases computer processing time, it gives a higher sense of reality to the user. **Video with Show Movement**[11] shows exactly how this possibility works.

Video without Show Movement[12] shows a simulation without movements being presented. By showing movements, it took approximately 38 seconds to present the final results. By not presenting movements, results took only eight seconds to be presented. A major difference in processing time (Appendix D shows computer specification as a reference).

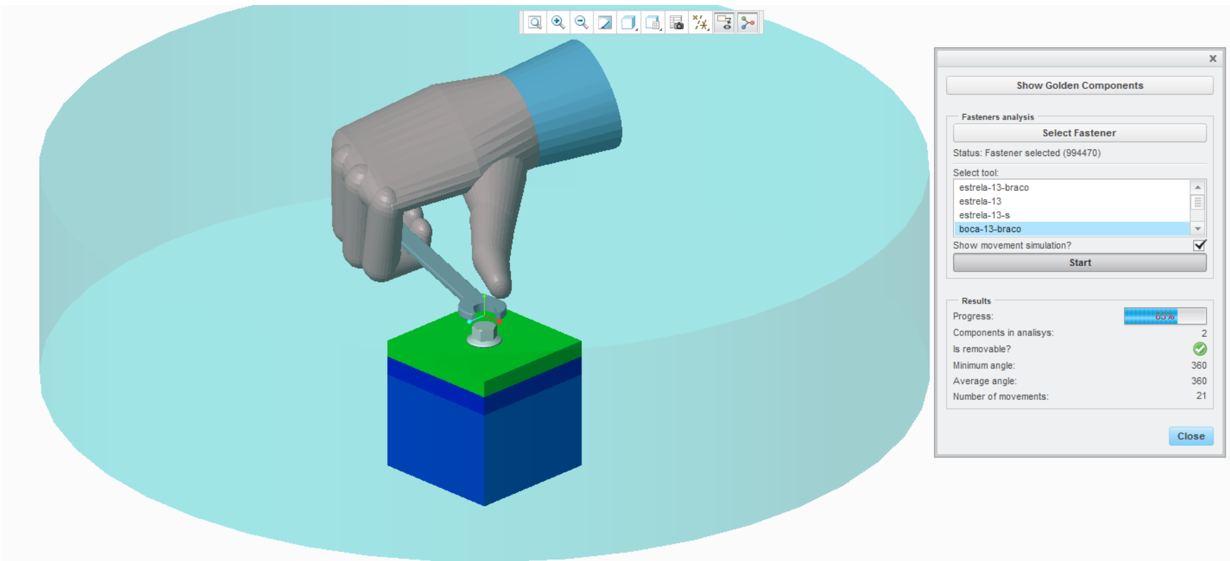


Figure 3.43 – Fastener analysis

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[11] Available on: <https://www.youtube.com/watch?v=l_DUwthfZfI&feature=youtu.be>. Access on: 05 Feb. 2017.
[12] Available on: <https://www.youtube.com/watch?v=nWTe7mcOHaU&feature=youtu.be>. Access on: 05 Feb. 2017.

3.5.1.2.1 Fastener analysis assumptions

Before exploring more this functionality, it is important to highlight some assumptions adopted on its usage:

a. Parts must be solids. Surfaces or cloud of points cannot be handled by the plug-in;

b. Fasteners must be connected to a second coordinate system (Figure 3.44 shows the secondary coordinate system – MNT, standing for “Maintenance”). This extra coordinate system is created on the fastener head in the position in which the universal tool is applied on. The “Y” axis has to be centered aligned with the fastener removal direction. The other two axis definition on the secondary coordinate system has no effect on the plug-in analysis;

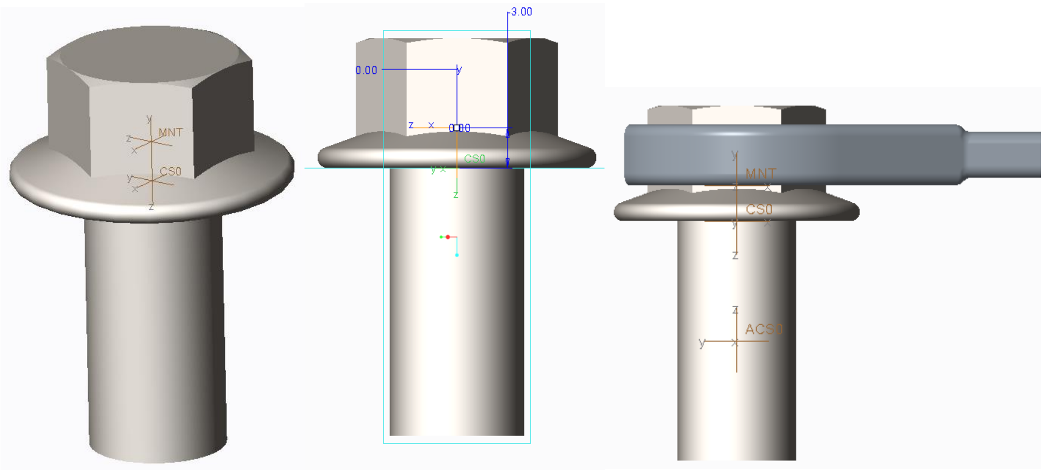


Figure 3.44 – Fastener second coordinate system - MNT

c. It is only possible to evaluate one fastener per time. To simplify the tool development no solution for multiple fasteners analysis was examined. Nevertheless, this is a possible future improvement;

d. The tool coordinate system has to be connected to the fastener secondary coordinate system. In other words, the tools must be modelled with its reference coordinate system in the same point as presented by MNT on Figure 3.44;

e. During the fastener removal analysis the plug-in does not consider the fastener removal itself. This is due to:

e.1. Avoid unnecessary fastener thread interferences with its counterpart during the fastener removal simulation;

e.2. It is also taken for granted that by simulating the tool removal movements the necessary space to remove the fastener is also included. The only drawback of such assumption is to have a pin on the top of the fastener head as proposed by Figure 3.23;

f. In the plug-in, the fastener entire length "**L**" (Figure 3.45) is considered in the simulation (no matter if in the reality the screw does not present thread throughout length "**L**");

g. In the plug-in, just screws are considered (on given examples in this thesis only flange screws have been used). Flange screws are used just as proof of concept. There was no intention during the study to be extensive in the number of tools and screws to be analysed. This does not limit though that other sort of screws and tools may be added to the database in the future.

3.5.1.2.2 Fastener specification

For the plug-in to work properly some specifications are mandatory to be provided. This works as a database showing the basic dimensions of a fastener.

On Figure 3.45 file used as a simple proof of concept (text file) shows fastener "994470" with a screw thread (**T**) equal to 1 mm and length (**L**) of 20 mm.

For the plug-in screw length (**L**) is considered to have a screw thread along the entire fastener.

Another step to structure the plug-in is to create a cross reference between tool and fasteners. This connection between screw nomenclature (Figure 3.46 SN) and possible tools nomenclatures (Figure 3.46 TN) to be used is provided via a simple text file (analogous to an enterprise databank). Figure 3.46 also shows an example of a hand and a regular wrench that is registered in the database when a user calls for this set.

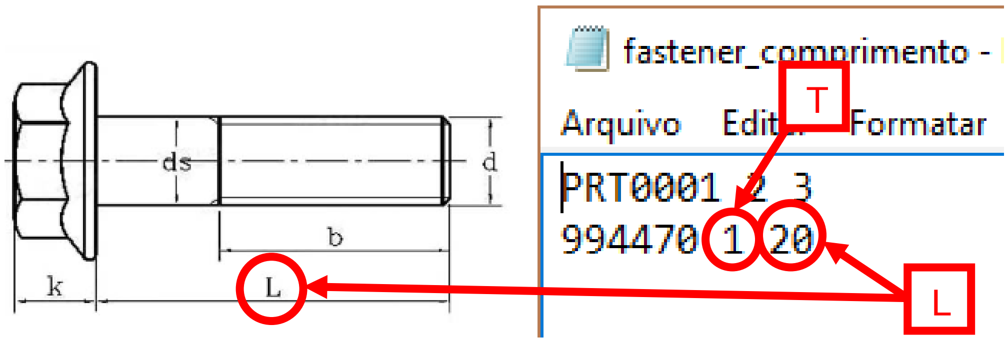


Figure 3.45 – Fastener dimension

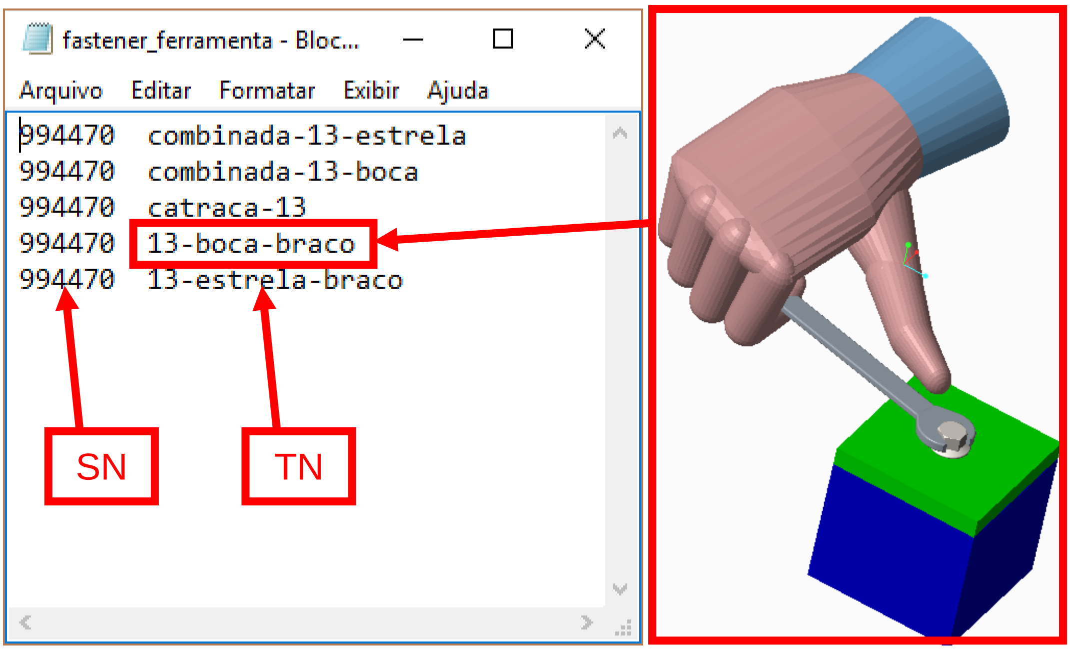


Figure 3.46 – Fastener and tools cross reference file

In the actual plug-in this connection may be seen as it is presented on Figure 3.47.

3.5.2 Plug-in configurations definitions

On Figure 3.37 user is presented with a Configurations button. By clicking on it, the window shown on Figure 3.48 is presented and the user has to select some important configurations.

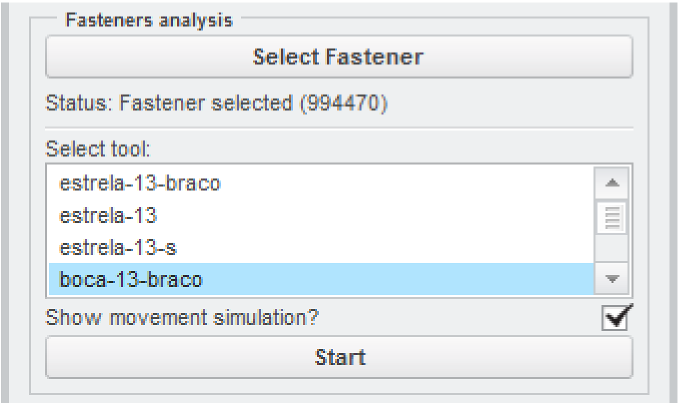


Figure 3.47 – Plug-in showing tools connected to a selected fastener

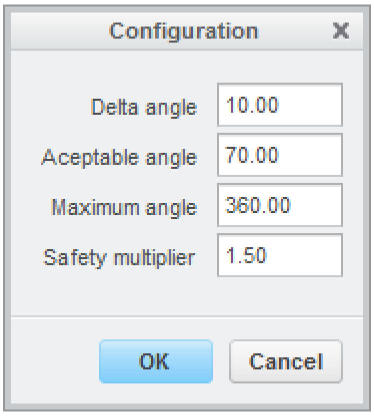


Figure 3.48 – Plug-in configurations window

The next sub-sections further explore these configurations.

3.5.2.1. Delta angle

Basically, to perform the maintainability analysis the plug-in evaluates if the hand and the tool volume in a certain position has any interference against to any other component in the analysis volume (see section 3.5.2.3 for further understanding on volume definition).

“**Delta angle**” (from Figure 3.48) determines the angle step that the interference analysis is performed on.

For example, if 90º angle is selected plug-in evaluates the interference in four different positions (360º divided 90º). As may be seen on Figure 3.49, if interference analysis is performed with a 90º delta angle there are plenty of empty spaces that possible components interferences could be missed.

If 60º is chosen, the result is presented on Figure 3.50. Even though two extra positions would be evaluated, it still presents too many areas without interference analysis.

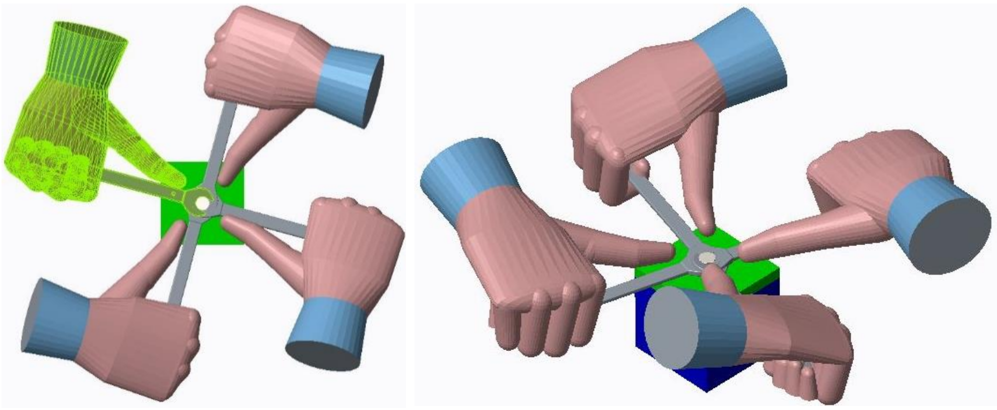


Figure 3.49 – Delta angle explanation – 90º

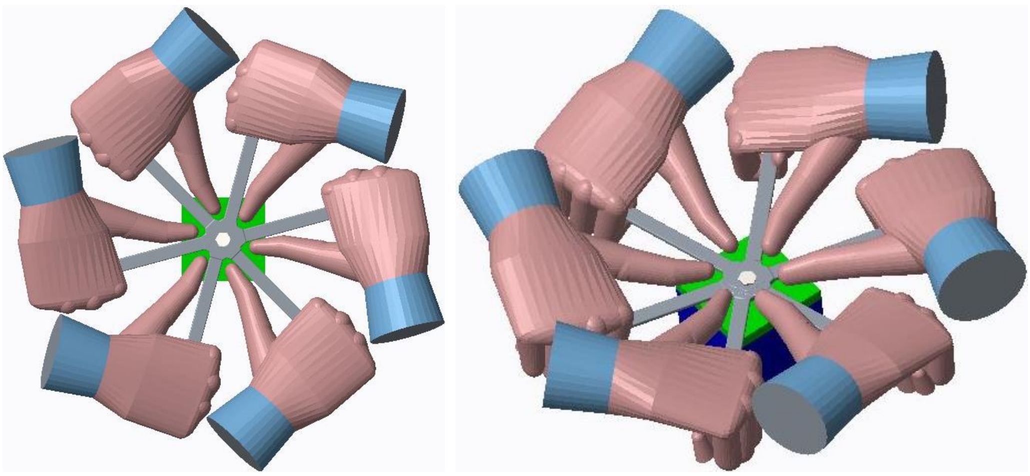


Figure 3.50 – Delta angle explanation – 60º

Figure 3.51 shows a 10º delta angle illustration. It is possible to conclude that with this delta angle nearly no spaces are left without interference.

The delta angle selection has two important aspects. High values of delta angles will reduce processing time, but will increase the interference analysis error. To lower delta values will increase processing time, but will assure more precise analysis results.

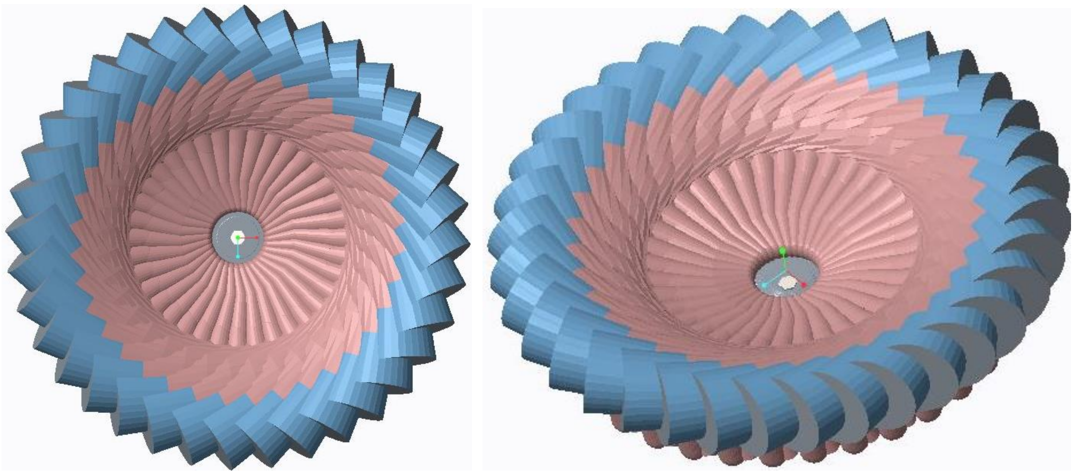


Figure 3.51 – Delta angle explanation – 10º

3.5.2.2. Acceptable and maximum angles

There are two other angles definitions which the plug-in user has to define. One is the “**Acceptable angle**”, and another is the “**Maximum angle**” (see Figure 3.48).

“**Acceptable angle**” is defined by the desire of the user of which is the angle value that mechanics normally prefer to apply when removing a fastener with a good maintenance space available (see section 3.1.1.1). From the interview performed this angle is defined as either 60º or 75º.

“**Maximum angle**” is the maximum angle of actuation when removing a fastener in the user perspective. Supposing that there is no interference when removing a fastener (360º free angle during the entire removal path), even in this scenario mechanics would never use the whole 360º if mechanics keep a standstill position holding the tool with all their fingers from one hand. With a standstill position and by holding the tool with all fingers a mechanic normally reaches a maximum angle of 120º (without moving his/her elbow too high) – see video[13]. On the practical test with the

[13] Available on: <https://www.youtube.com/watch?v=o5h-Np-k_Zo&feature=youtu.be>. Access on: 27 Feb. 2017.

mechanics presented on Appendix C, maximum value selected by the majority of participants was either 90º or 120º.

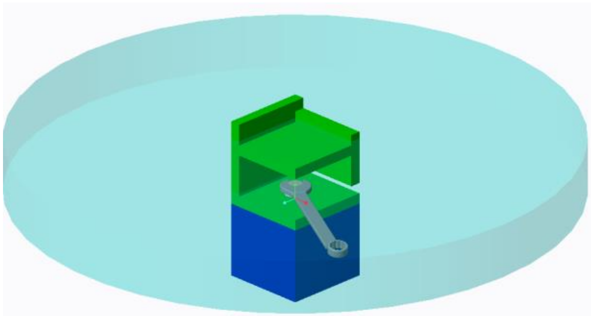
A possible 360º movement may be made if the mechanic starts by breaking the torque – loosen the screw by holding the tool with all fingers from one hand and after that starts to unscrew the fastener with just one finger (see “Video loosen a screw with open 360 degrees”[14]). This possibility is not covered by the plug-in though.

3.5.2.3. Safety multiplier

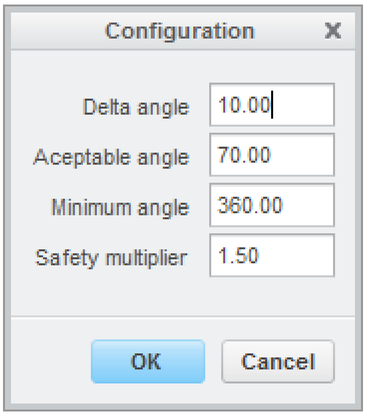
Complex products such as commercial vehicles, airplanes, passenger cars or trains contain some thousands of parts. Would it be really feasible to perform an oil filter removal analysis comparing interferences against the entire product? Definitely not, as it would require too much computer processing time.

Therefore, based on an idea from IPS system (Figure 2.38) which uses a volume to narrow down the analysis of a part path planning removal, the plug-in here examined also uses a maintainability analysis volume to reduce computer processing time in order to evaluate components’ interferences. All parts from the CAD module that are totally or partially inside of such volume is analysed (interference analysis).

This volume (Figure 3.52) is defined based on the tool and hand size.



a/ Volume considered for analysis



b/ Configuration window

Figure 3.52 – Interference volume analysis

[14] Available on: <https://www.youtube.com/watch?v=RZmBYFaQV2w&feature=youtu.be>. Access on: 27 Feb. 2017.

From the fastener reference coordinate system (MNT) the height ("**h**" - Figure 3.53) of the cylinder volume is the sum of "**dy1**" (from reference to highest point of hand and tool) and "**dy2**" (from reference to lowest point of hand and tool) plus the screw length ("**L**" – from Figure 3.45). There, the height presented on Figure 3.53 may be expressed by the equation 6:

$$h = dy1 + dy2 + 1 + L \quad (6)$$

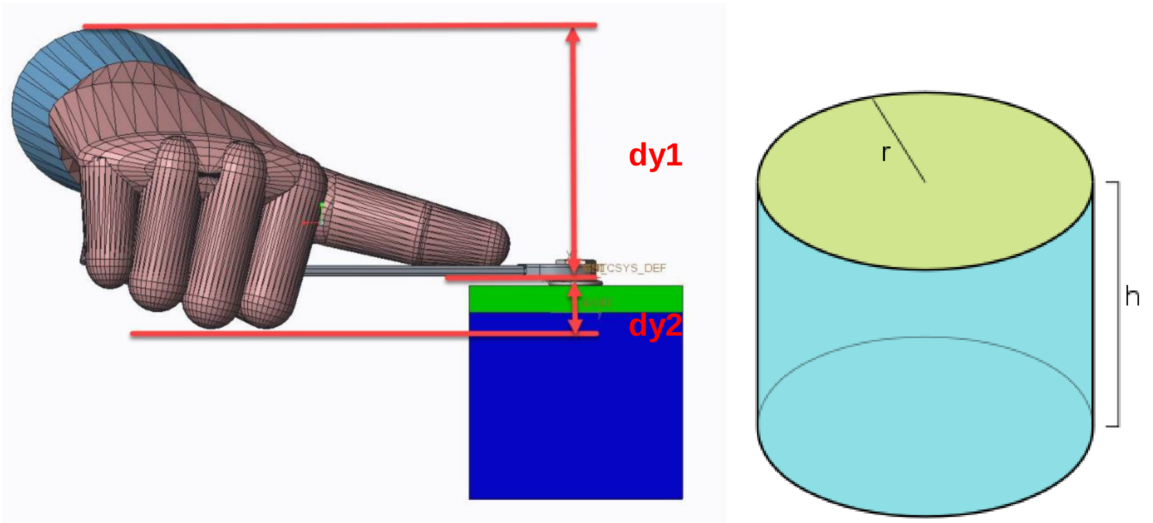


Figure 3.53 – Volume height

From the fastener reference coordinate system (MNT) the radius ("**r**") of the cylinder volume is defined by the farthest point of the volume composed by hand and tool (Figure 3.54).

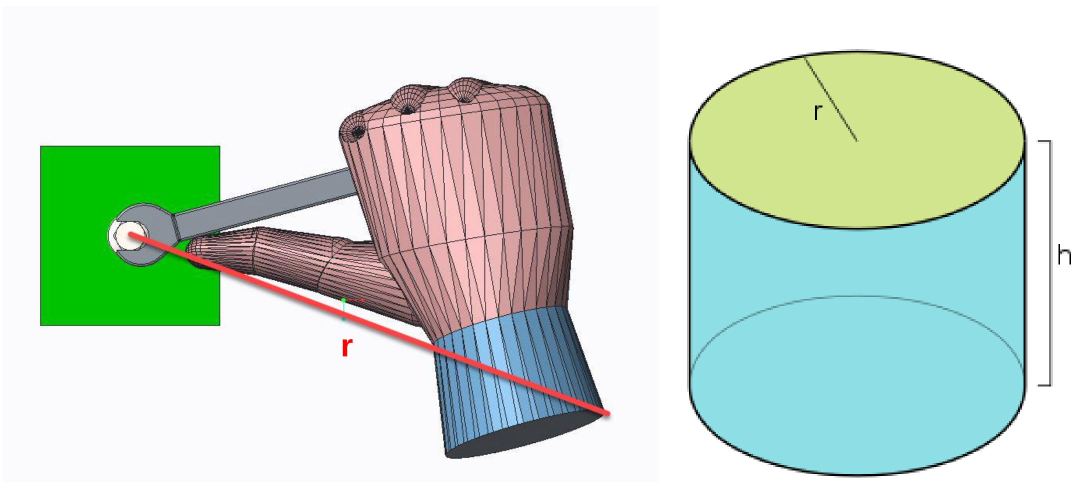


Figure 3.54 – Volume radius

When selecting a safety multiplier the user may increase the volume of interference analysis.

Example of a volume height with a safety multiplier equal to 1 is given on Figure 3.55.

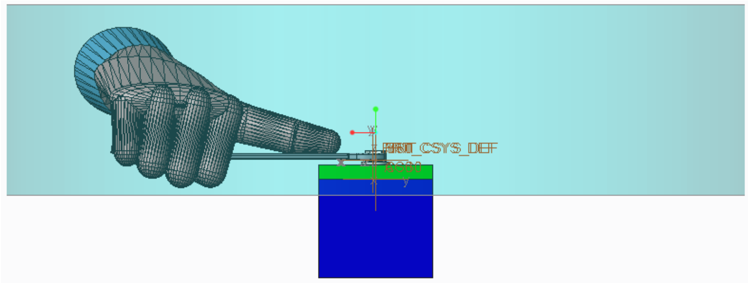


Figure 3.55 – Volume height with safety multiplier equal to 1

Example of a volume radius with a safety multiplier equal to 1 is given on Figure 3.56.

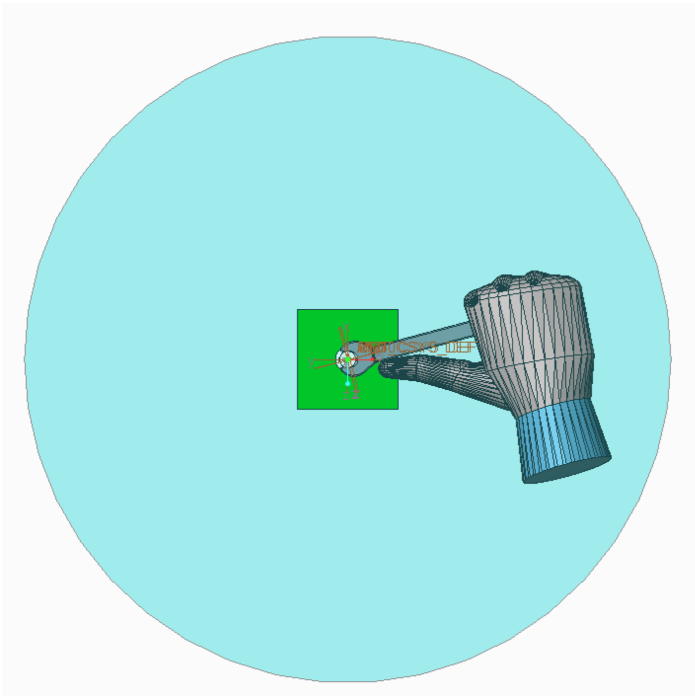


Figure 3.56 – Volume radius with safety multiplier equal to 1

Example of a volume height with a safety multiplier equal to 2 is given on Figure 3.57.

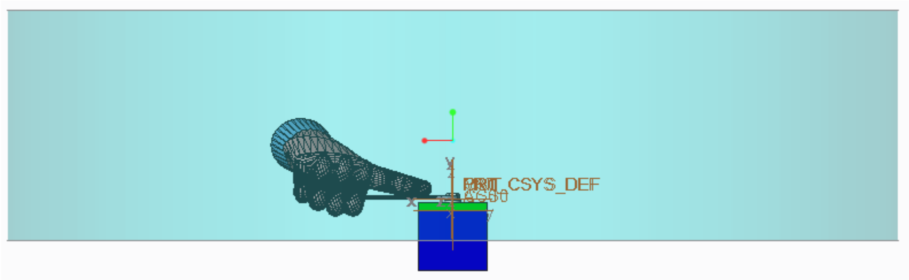


Figure 3.57 – Volume height with safety multiplier equal to 2

Example of a volume radius with a safety multiplier equal to 2 is given on Figure 3.58.

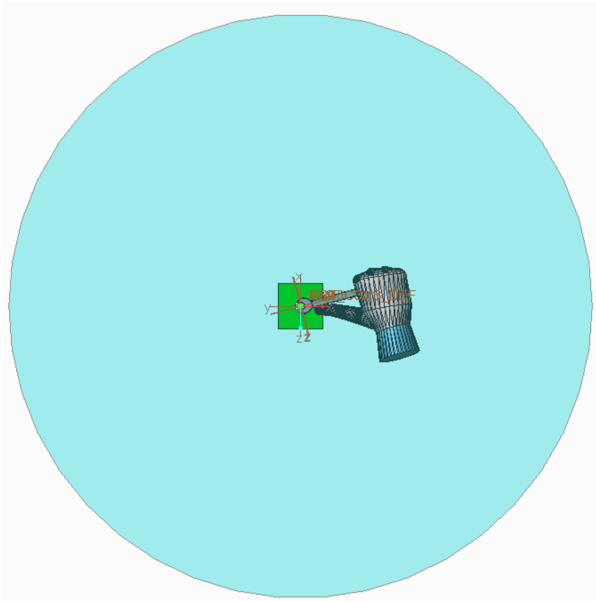


Figure 3.58 – Volume radius with safety multiplier equal to 2

3.5.3 Results

In the plug-in window (Figure 3.38) analysis result is also expressed. In the results area six fields of information are presented.

Firstly, there is a progress bar. It shows the progress percentage throughout the entire analysis (example of a 100% progress bar on Figure 3.59).

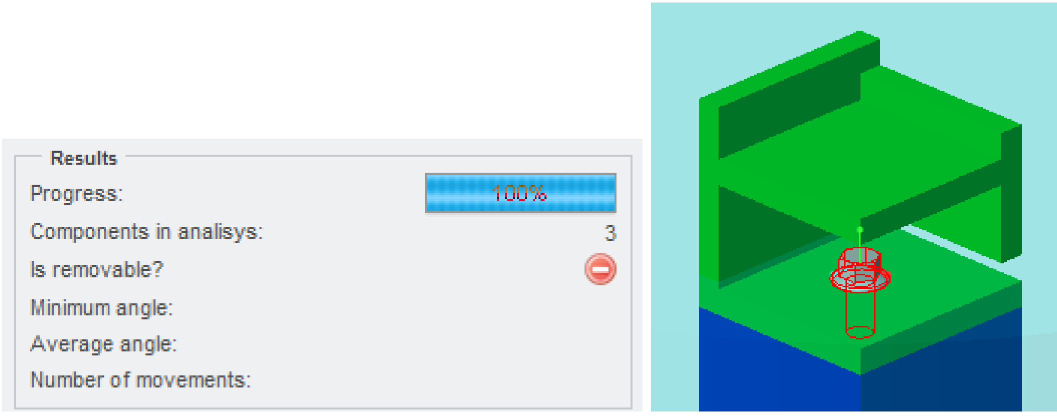


Figure 3.59 – Fastener not removable

Second field is “**Components in analysis**”. It shows how many components are being considered for the maintainability interference analysis. This value is directly defined by the parts that interfere with the volume described on Figure 3.52.

The next information is a sign showing the status of the removal analysis (Figure 3.60). A red sign shows that removal is not possible. Yellow exclamation sign presents a possible removal with the tool selected but with available angle less than the acceptable angle (explained earlier). And the green sign stating a possible fastener removal within the acceptable angle value.

Figure 3.60 – Fastener analysis signs

Additionally to the signs above, fastener is also converted to the same colours, indicating the removal analysis result. Figure 3.59 shows a fastener in a red colour, indicating it is not possible to remove it. Figure 3.61 presents a possible removal but with lower average angle compared to acceptable angle value declared in the configurations window (Figure 3.48). Figure 3.62 shows a fastener in green colour stating a possible removal with the tool selected.

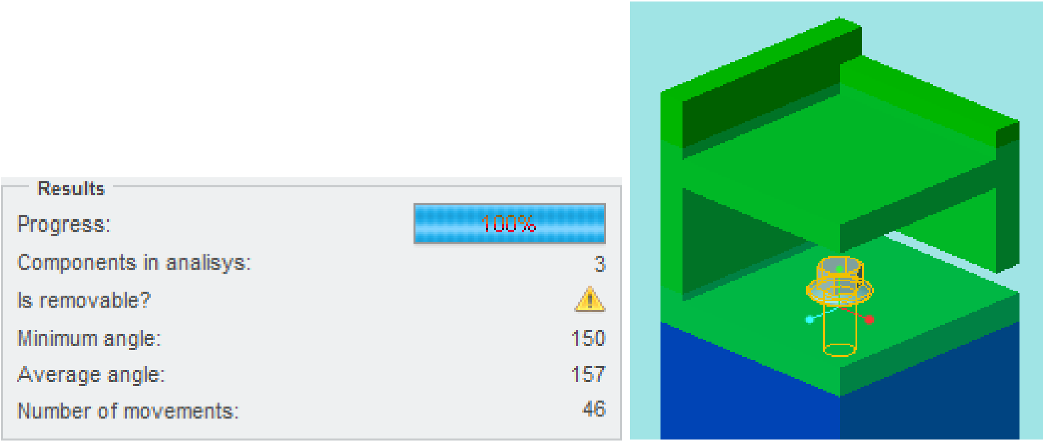


Figure 3.61 – Fastener removable but with less than acceptable angle

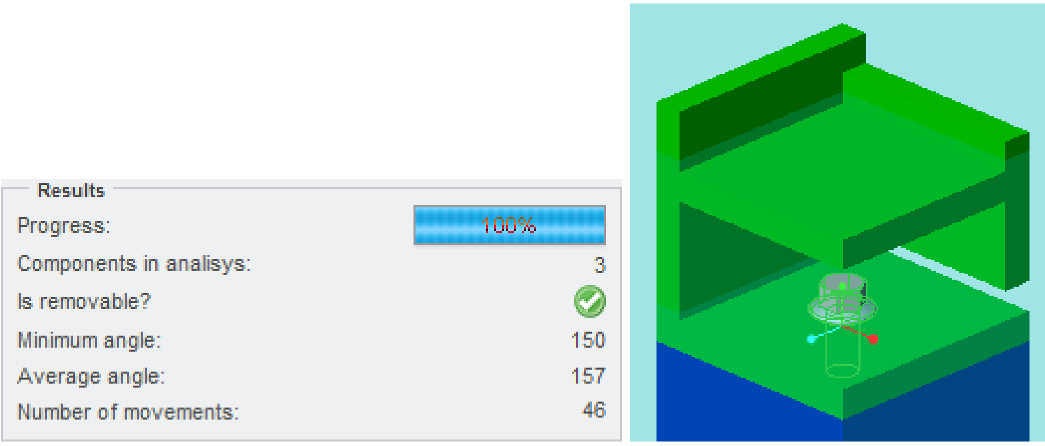


Figure 3.62 – Fastener possible to be removed

Another result value presented is the "**Minimum angle**" (Figure 3.62). It presents the minimum angle movement found in the simulation. Then the "**Average angle**" result just shows the average rotation movement found along the total "**Number of movements**" that were necessary to remove the complete screw length.

4 MODEL VERIFICATION AND VALIDATION

In order to verify and validate this research, it is important to understand how the new model proposed will influence the designers and which outcomes it will result.

The verification and validation chapter is divided in four major sections.

First one shows the plug-in verifications performed against the validation models from Table 3.2. Focus is to evaluate the function of “Fastener Analysis” on this first section. The following test sequence is performed on different validation models:

a. Star spanner with and without visualization;

b. Regular wrench with and without visualization;

c. Ratcheting wrench with and without visualization;

d. Star spanner + P95 hand with and without visualization;

e. Regular wrench + P95 hand with and without visualization;

f. Ratcheting wrench + P95 hand with and without visualization.

Within the same section three “Configuration” functionalities from the plug-in are tested: i/ Delta angle; ii/ Acceptable angle; and iii/ Maximum angle.

On the second section, CAD module from Popescu and Iacob (2013) presented on Figure 3.25 is used as a base to verify and validate the access level of different fasteners. The safety multiplier configuration, golden components and number of components functionalities are verified in this section.

The third section presents a comparison between Junior (2015) verification module (Figure 3.29) and the current thesis model.

These three sections were performed in order to verify the maturity level of the thesis model, developing it further when failures or possible improvements were found.

The fourth and last section shows a verification and validation of the maintainability model with a group of engineers which have used or not the plug-in in a test-bed case. It presents the benefits and limitations that the proposed model offers based on a survey collected from the engineers after the model usage.

4.1 Removal barriers – validation models

The plug-in verification started with the validation models earlier proposed on Table 3.2.

4.1.1 Free angle of actuation

First item presented is "Free angle of actuation" (see Figure 3.11). As earlier described, on this scenario a free 360º angle is offered. Therefore, no issues were found during the verification procedure.

Configuration values were set as expressed on Figure 4.1. These values were used as a reference during this section.

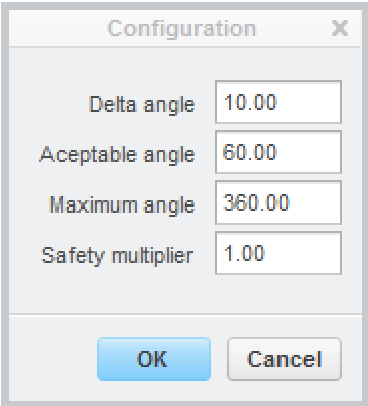


Figure 4.1 – Verification test: configuration values

First step was to click on "**Select Fastener**", and after click on the actual fastener using the mouse command.

Note: fastener had to have a secondary coordinate system denominated "MNT" (Figure 4.2). If this secondary system is not found, system replies with a fatal error.

Then, with fastener selected based on the databank created, a set of tools were presented to the user.

A try-out with a start spanner was the first action with "**Show movement simulation**" selected. It took approximately 27 seconds for the plug-in to conclude that it was possible to remove selected fastener (by presenting it on a green colour format) and showing the result on the plug-in itself (see Figure 4.4). By removing the simulation visualization possibility this time period was reduced to just two seconds.

Note: Appendix D shows computer specification as a reference for time stamps achieved.

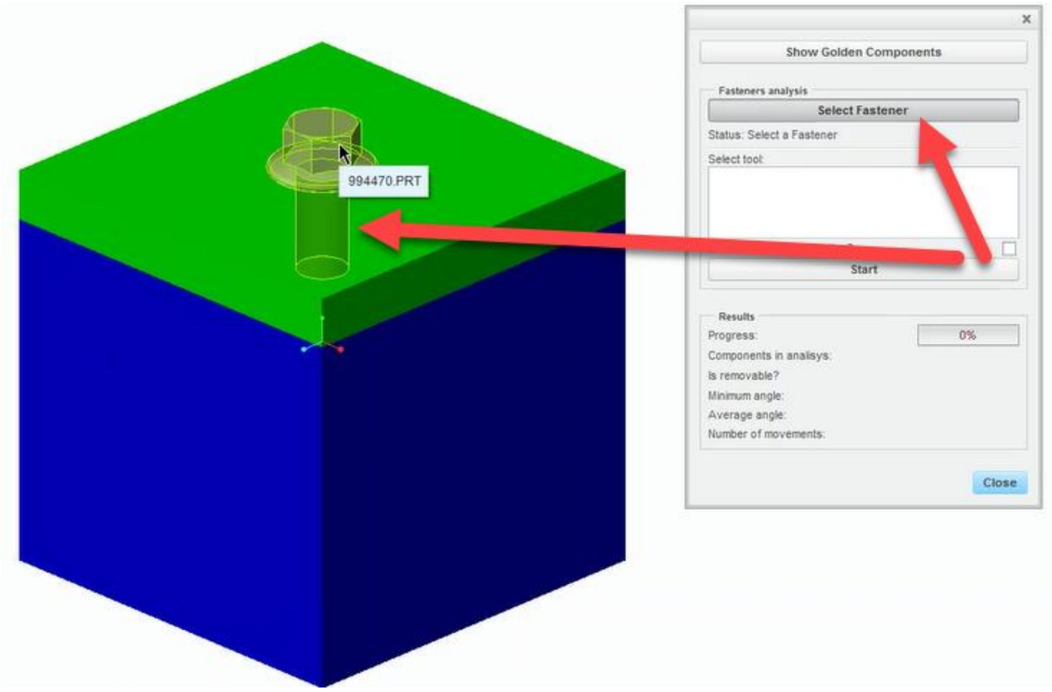


Figure 4.2 – Option: select fastener

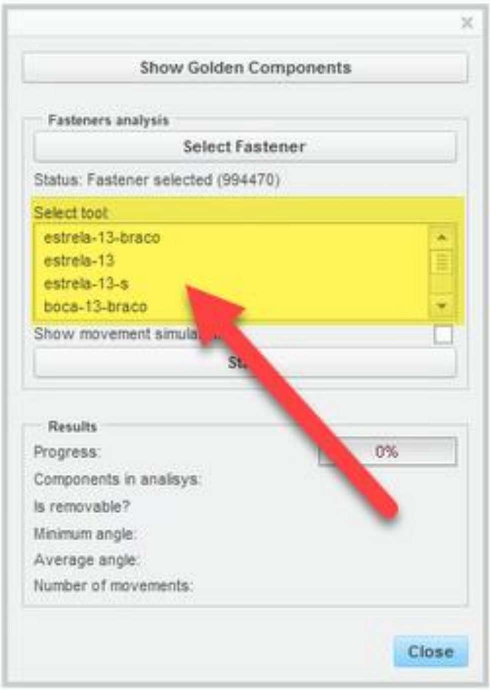


Figure 4.3 – Select Tool

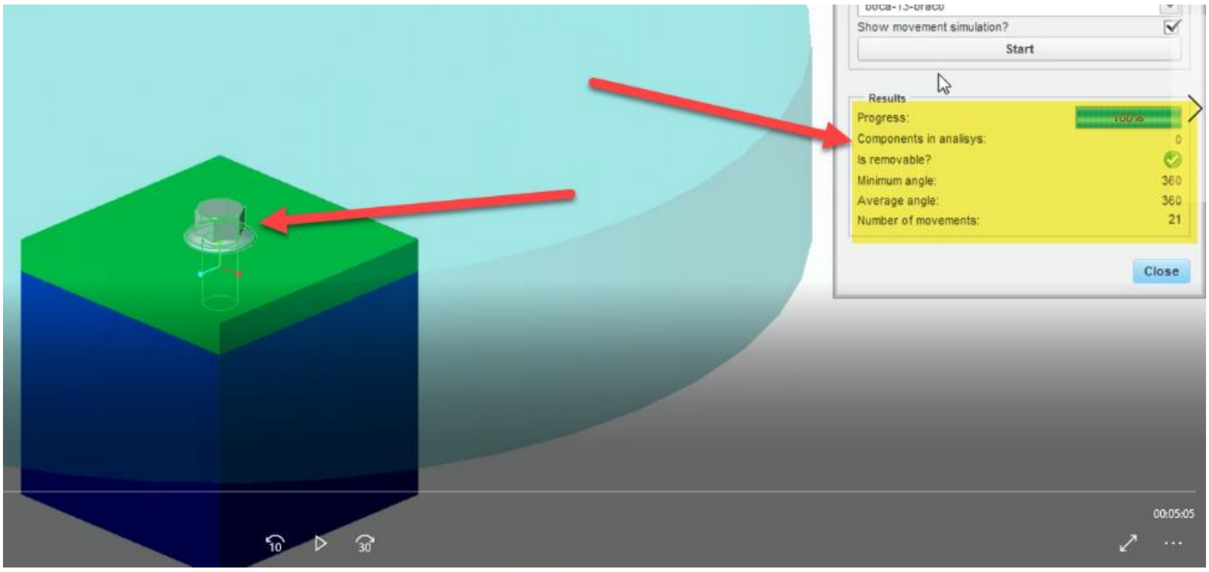


Figure 4.4 – Result with show movement simulation

The same procedure was repeated with the other side of the tool by selecting a wrench (26 seconds with visualization and two seconds without) and also by choosing a ratcheting wrench (25 seconds with visualization and two seconds without).

The whole “Free angle of actuation” verification is found on video[15]. In the same video the test procedure was repeated now with the P95 hand included (Figure 4.5). With visualization included and testing with a star spanner the result was presented after 45 seconds (extra 17 seconds if compared to the simulation without a hand). Without visualization the same procedure demanded 6 seconds only. Video continues with wrench and ratcheting wrench with hand included (with similar results).

4.1.2 Angle constraint

Moving to angle constraint type of barrier was the first real test to verify and validate if the plug-in would really comprehend the maintenance space available. Figure 4.6 presents the barrier dimensional as the basis for the analysis.

Following the same sequence as the “Free angle of actuation” test, the following try-outs were performed:

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[15] Available on: <https://www.youtube.com/watch?v=7-7Iw3aoQRQ&feature=youtu.be>. Access on: 14 Feb. 2017.

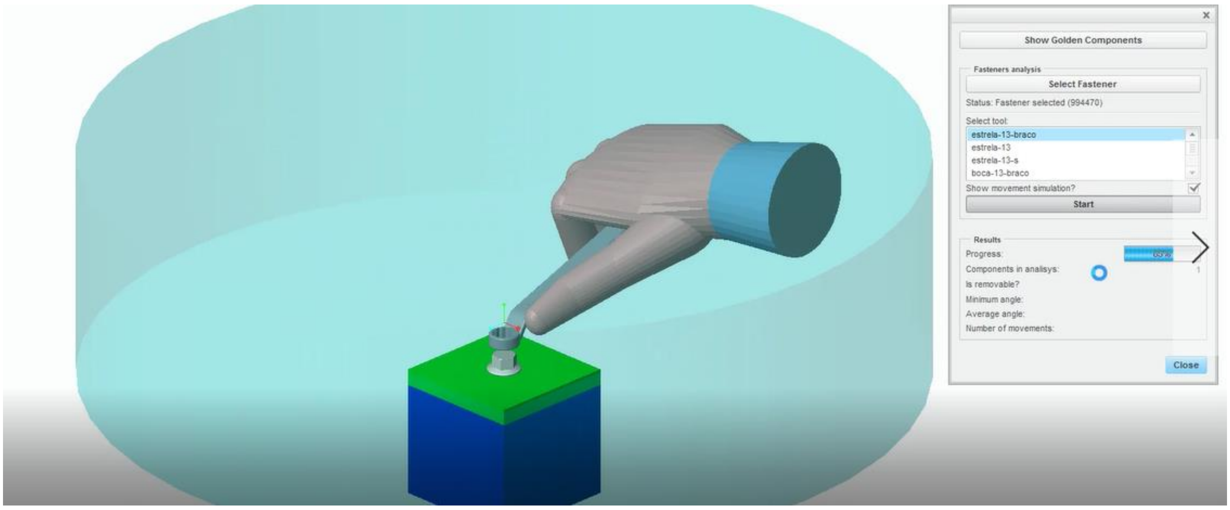

Figure 4.5 – Simulation with P95 hand included

a.Star spanner with and without visualization;

b. Regular wrench with and without visualization;

c. Ratcheting wrench with and without visualization;

d. Star spanner + P95 hand with and without visualization;

e. Regular wrench + P95 hand with and without visualization;

f. Ratcheting wrench + P95 hand with and without visualization.

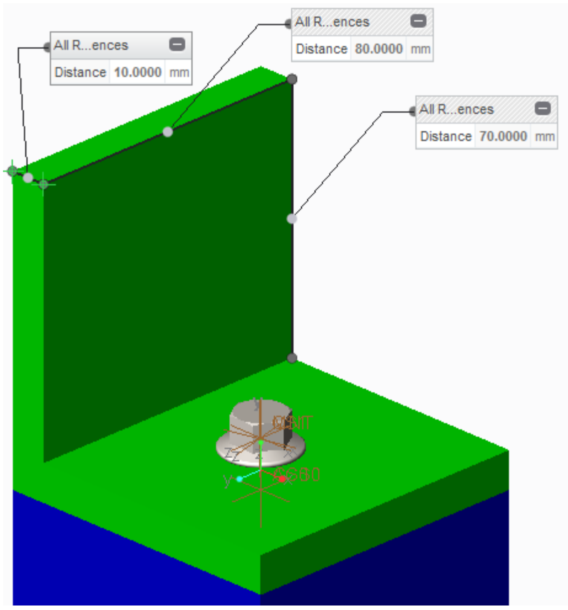

Figure 4.6 – Dimensional of Angle constraint barrier

With all possibilities above screw was considered as possible to be removed. Video “Angle of Constraint 1”[16] shows all steps taken during the verification. Table 4.1 presents the results found.

Table 4.1 – Angle constraint barrier

	Time stamp (seconds)					
Tool type	**With Visualization**	**Without Visualization**	**Time difference comparison (%)**	**P95 Hand With Visualization**	**P95 Hand Without Visualization**	**Time difference comparison (%)**
Star spanner	41	6	14,6%	48	21	43,8%
Wrench	34	6	17,6%	51	25	49,0%
Racheting wrench	34	6	17,6%	41	7	17,1%
Possible to remove?	Yes	Yes	16,6%	Yes	Yes	36,6%

Some specific points though need to be highlighted:

a. It is recognisable that there is a great analysis gain to perform the evaluation without visualization. It normally took 17% of the time performing the analysis without visualization;

b. This time though was increased to around 46% when a processing error was presented (illustrated on Figure 4.7). This happened on two simulations: i/ P95 Hand without visualization – star spanner; ii/ P95 Hand without visualization – wrench. The results prompted with or without visualization were exactly the same though. In fact, this was found to be a Windows (Trademark) interpretation that plug-in would have stopped. As the plug-in does not generates any graphical processing demand, PTC Creo interprets that the program might have stopped which in fact was not the case;

c. Another point to be considered was the difference found on the number of components expressed on the Figure 4.8 results (as example). Comparing Figure 4.9 and Figure 4.10 it is understood that the maintainability analysis volume (see further information on section 3.5.2.3) captures a different number of components due to the tool shape. With star spanner, volume does not include the blue box. As with a regular wrench, blue box is included.

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[16] Available on: <https://www.youtube.com/watch?v=q9HQEFDpv9Q&feature=youtu.be>. Access on: 19 Feb. 2017.

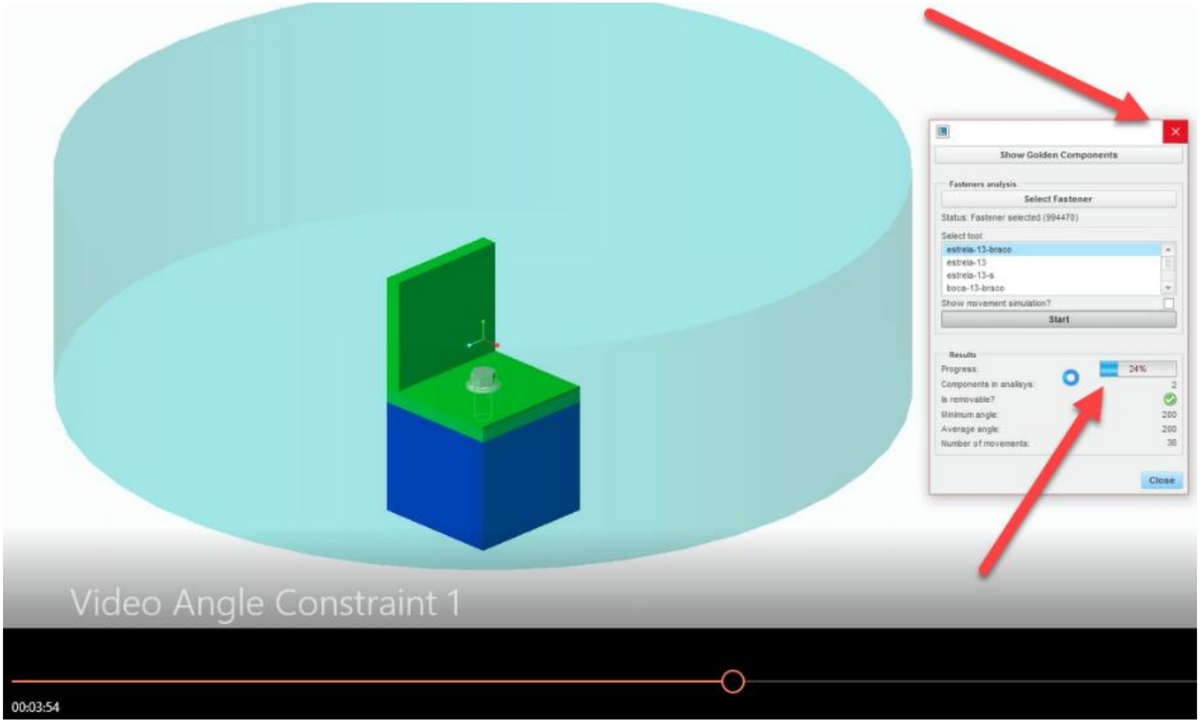


Figure 4.7 – Plug-in visualization error

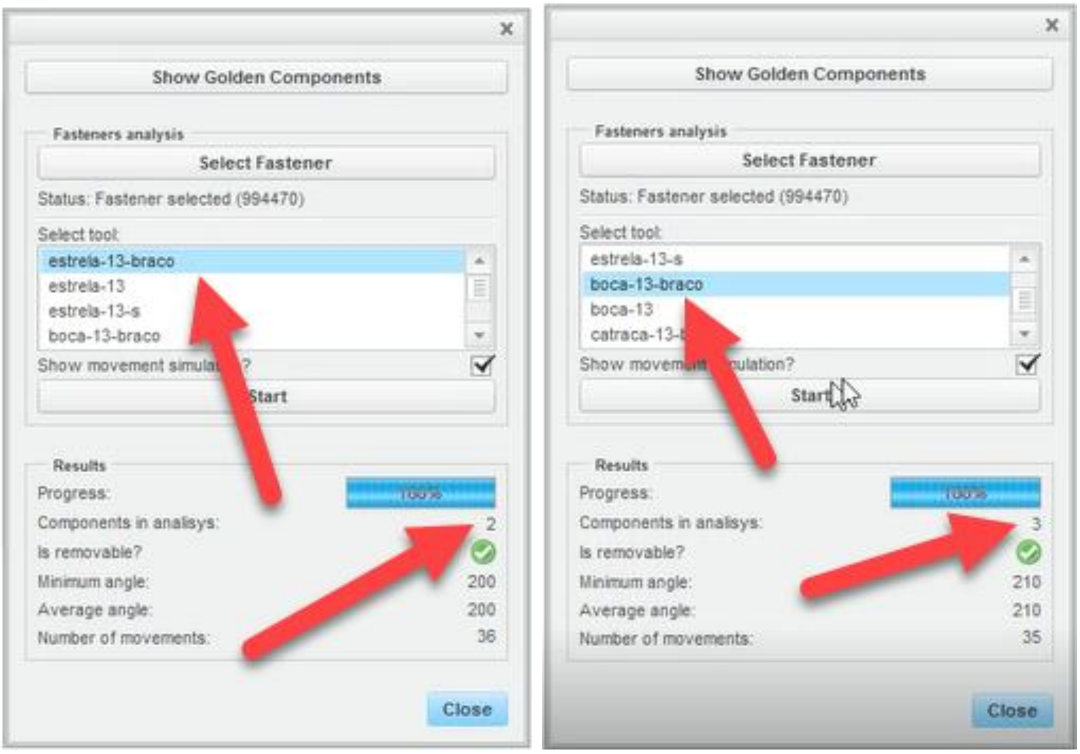


Figure 4.8 – Difference on number of components results

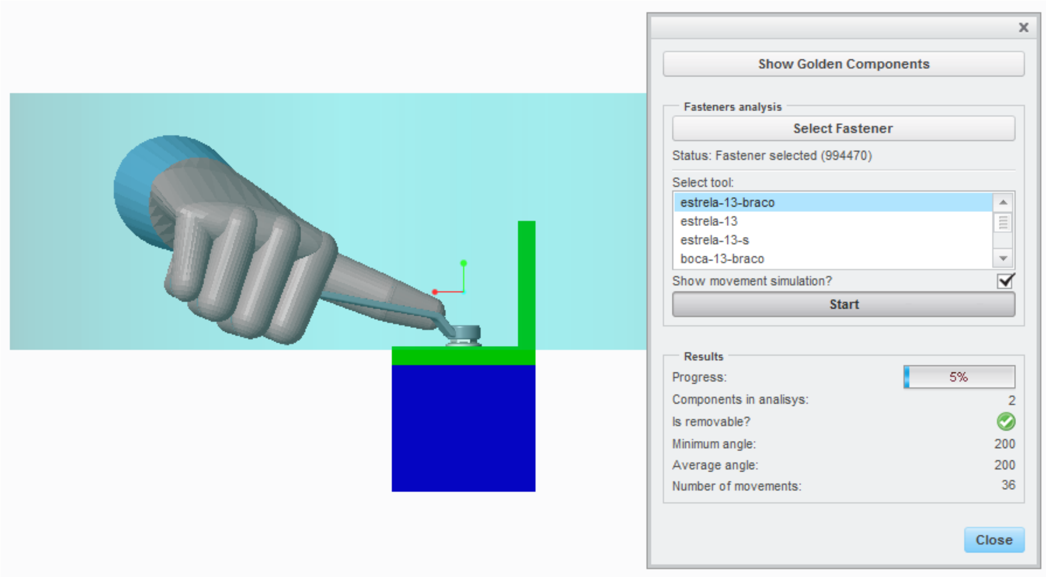


Figure 4.9 – Maintainability analysis volume – star spanner

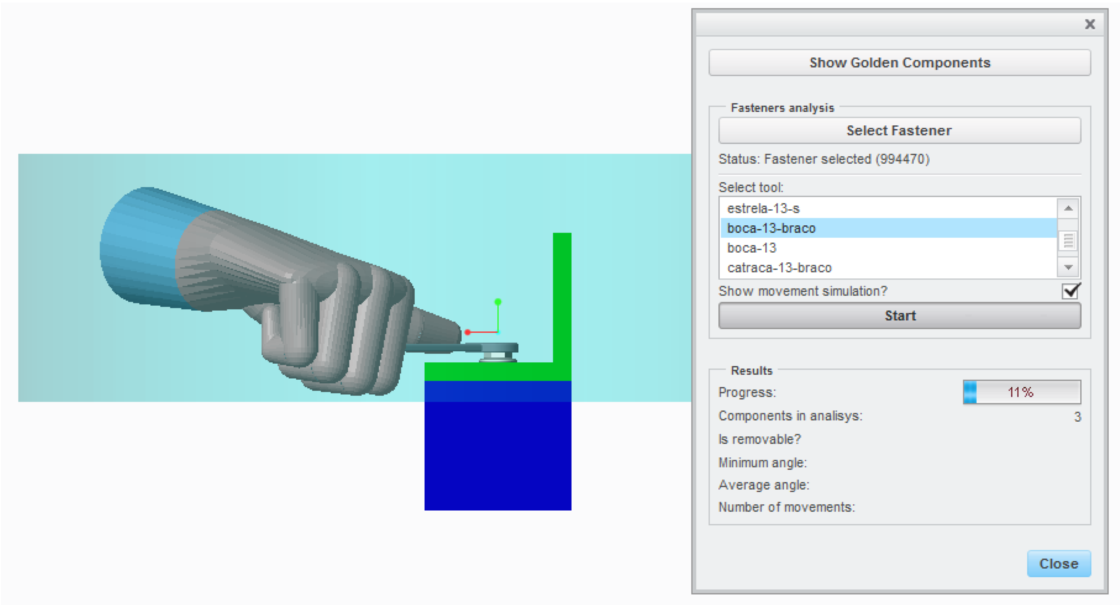
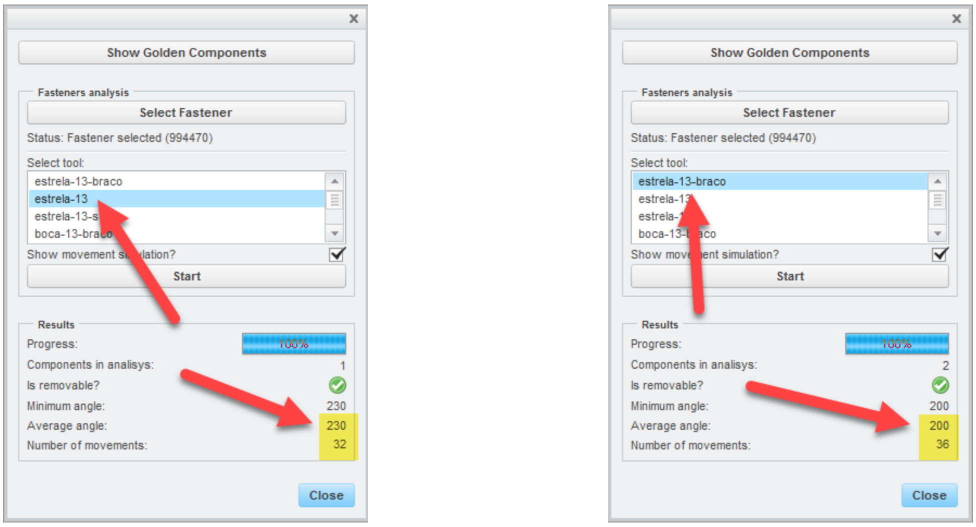


Figure 4.10 – Maintainability analysis volume – wrench

d. Another example of differences found on the results was the average angle and number of movements. As example star spanner with and without a P95 hand the result difference presented extra 30º without a hand and four additional movements with a hand included in the analysis (Figure 4.11). Video "Number of movements and average angle"[17] shows the difference between the analysis with

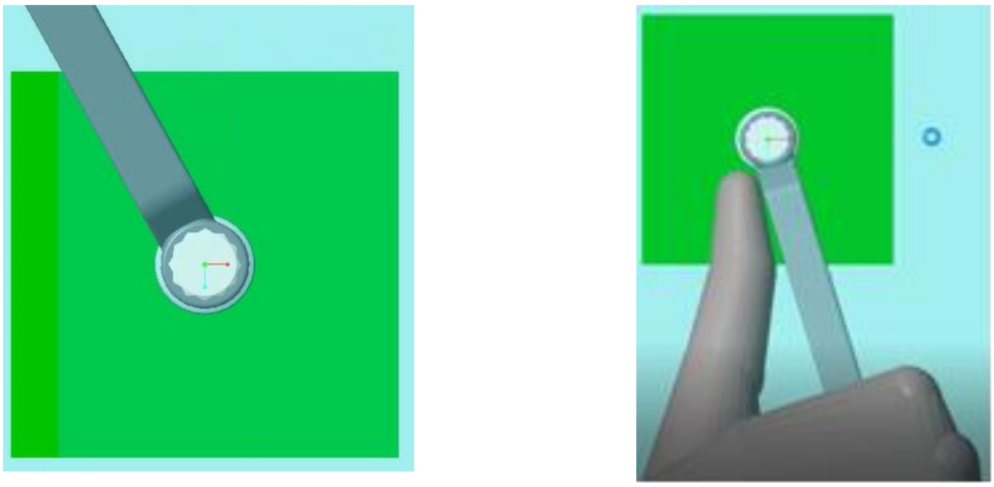
[17] Available on: <https://www.youtube.com/watch?v=t6MqkCK2QQY&feature=youtu.be>. Access on: 19 Feb. 2017.

and without a hand. In order to form a more precise explanation, Delta angle configuration was changed to just 1º. Figure 4.12 show that with a hand included, angle is reduced due to the presence of a finger which requires more space than just a regular tool. Due to that, number of movements also increases.



a/ Star spanner analysis only b/ Star spanner with a hand analysis

Figure 4.11 – Comparison between average angle and nº of movements



a/ Tool analysis without a hand b/ Analysis with a hand included (finger requires space)

Figure 4.12 – Average angle and number of movements with and without a hand

As presented on Table 3.2, another Angle constraint is proposed – details on Figure 4.13.

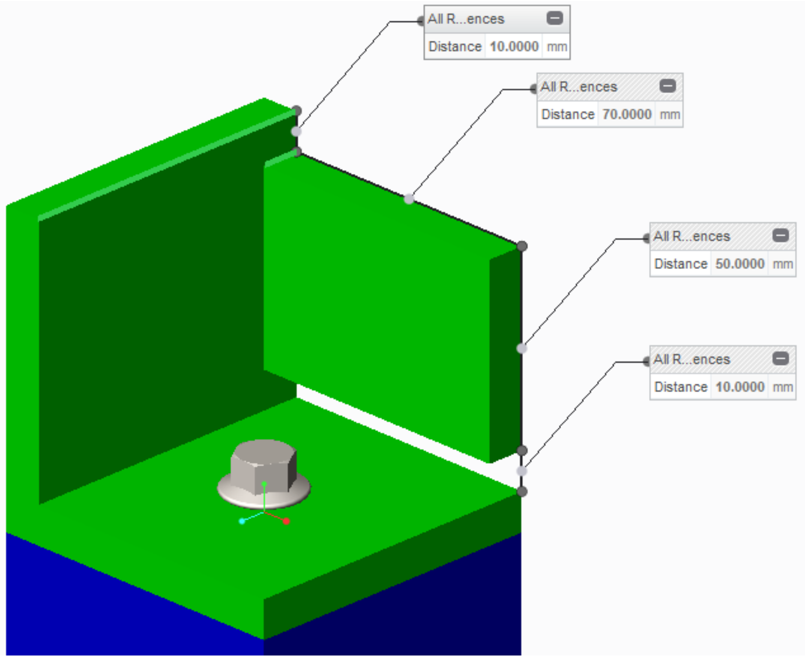


Figure 4.13 – Dimensional of angle constraint barrier – extra lateral barrier

This second type of Angle constraint is presented on the "Video Angle Constraint 2"[18]. Figure 4.14 shows one simulation point presented on the video.

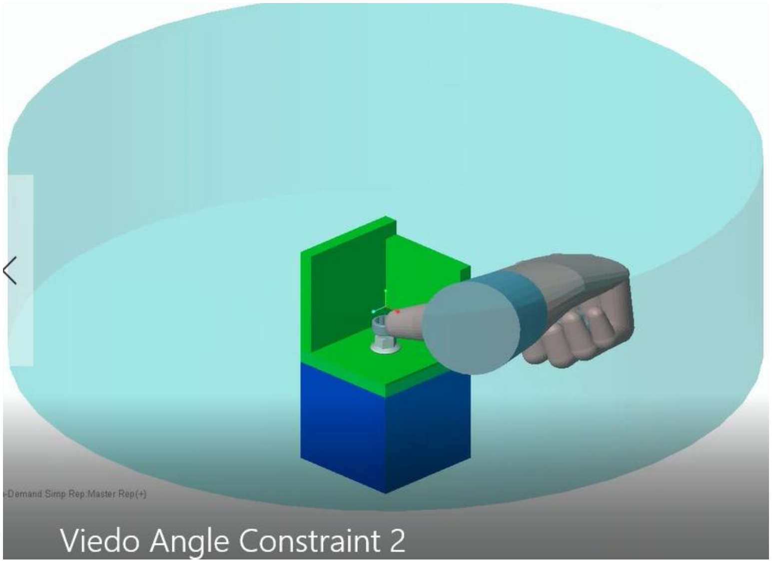


Figure 4.14 – Angle constraint barrier – video image sample

Interesting aspect of this constraint is to compare star spanner and regular wrench simulations. With a regular wrench, the tool itself is able to find a space

[18] Available on: <https://www.youtube.com/watch?v=Ibr-vLiD7XY&feature=youtu.be>. Access on: 19 Feb. 2017.

underneath the barrier (Figure 4.15) which is not possible with a star spanner. In the end, when results were actually presented, it was possible to compare this difference by the average angle and movements (Figure 4.16). Average angle was greater and number of movements was lower in favour of the regular wrench.

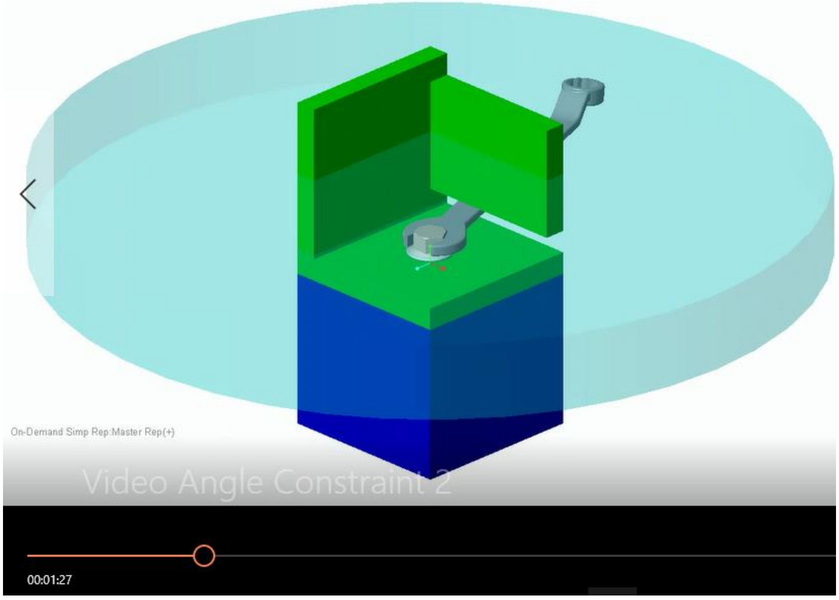
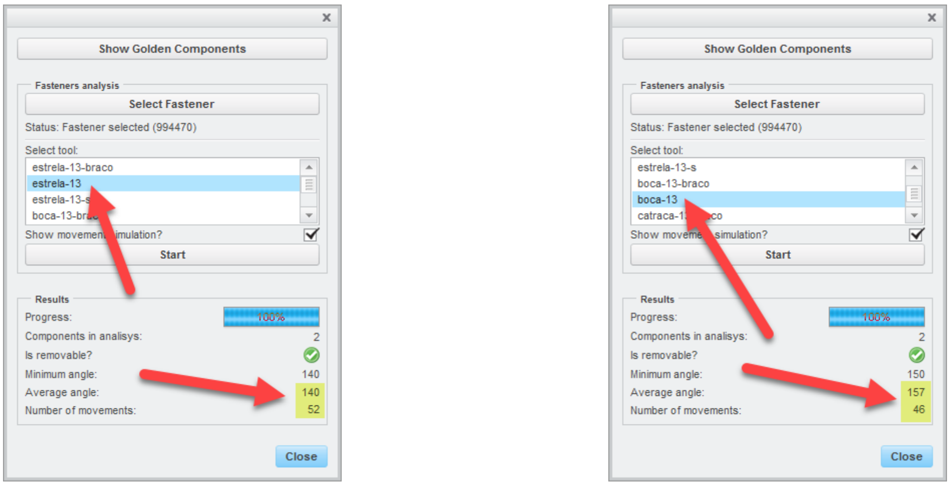


Figure 4.15 – Wrench under the barrier



a/ Star spanner evaluation b/ Wrench evaluation

Figure 4.16 – Angle constraint - Results comparison

Similar aspect was observed with a ratcheting wrench as this is a bigger tool, so by the end of the simulation, tool may be seen above the barrier (Figure 4.17).

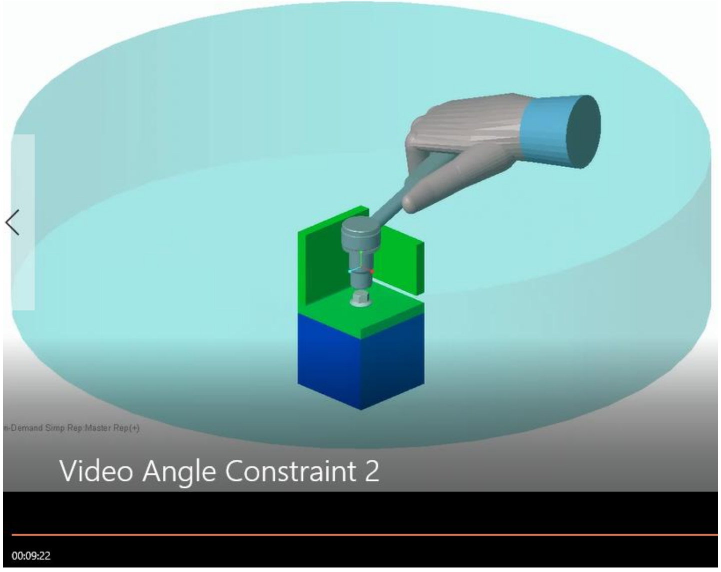


Figure 4.17 – Ratcheting wrench above the barrier

The results achieved with this type of barrier are expressed on Table 4.2. The same processing error presented on Figure 4.7 was repeated several times whenever an analysis without visualization was selected. However, it was still possible to confirm that it was much faster to perform the simulation without visualization.

Table 4.2 – Angle constraint barrier 2 (extra lateral barrier)

	Time stamp (seconds)					
Tool type	**With Visualization**	**Without Visualization**	**Time difference comparison (%)**	**P95 Hand With Visualization**	**P95 Hand Without Visualization**	**Time difference comparison (%)**
Star spanner	45	14	31,1%	80	52	65,0%
Wrench	45	14	31,1%	86	61	70,9%
Racheting wrench	42	13	31,0%	47	19	40,4%
Possible to remove?	Yes	Yes	31,1%	Yes	Yes	58,8%

Just as a case study, another test that was performed was to simulate a screw length of 100 mm instead of the real 20 mm (Figure 3.45). Test was performed with a regular wrench only in order to capture if the plug-in would indeed comprehend all the available spaces along the exit route. Figure 4.18 shows a maintainability analysis volume much bigger coping with a 100 mm screw length.

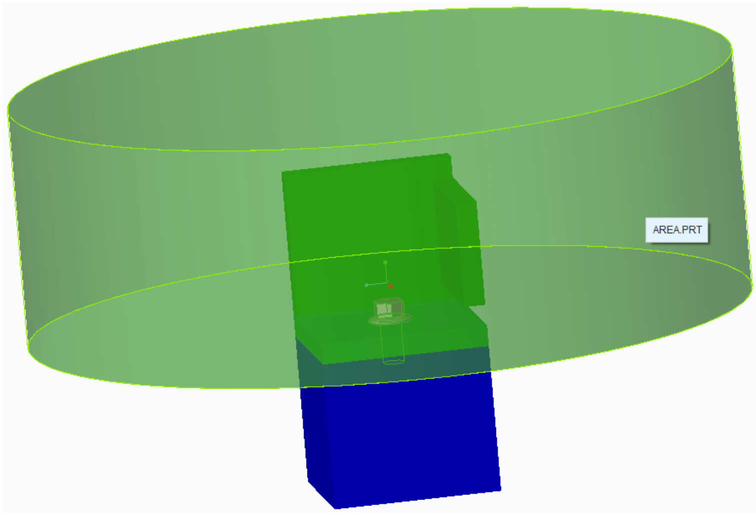


Figure 4.18 – Longer simulated fastener – plug-in functionality check

The plug-in did actually observed all space available respecting the angle constraints and using a complete 360º angle when it was possible. This is confirmed by the “Video Angle Constraint simulation with longer screw”[19]. Figure 4.19 shows different simulations points presented on the video.

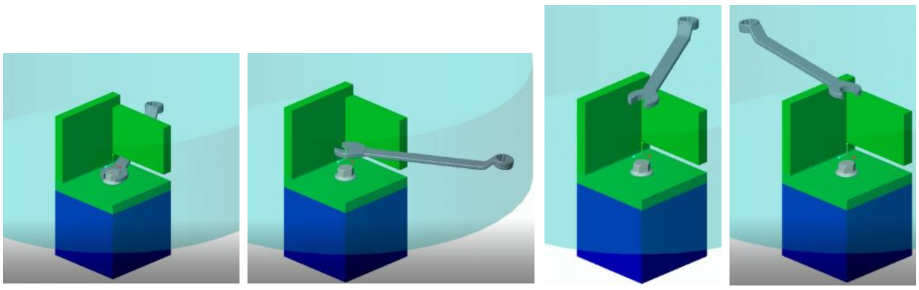


Figure 4.19 – Angle constraint simulation with longer screw – video image samples

4.1.3 Top Barrier

Top barriers were other types of obstacles used to verify and validate the proposed plug-in. Three different top barriers were examined (as per Table 3.2) – 20 mm, 40 mm and 90 mm.

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[19] Available on: <https://www.youtube.com/watch?v=QRPhHOh_OnU&feature=youtu.be>. Access on: 26 Feb. 2017.

4.1.3.1. Top Barrier – 20 mm

As a start, 20 mm top barrier was tested. Following the same sequence as the "Angle constraint" test, the cases were performed and are expressed on Table 4.3:

Table 4.3 – Top barrier with 20 mm

	Time stamp (seconds)					
Tool type	**With Visualization**	**Without Visualization**	**Time difference comparison (%)**	**P95 Hand With Visualization**	**P95 Hand Without Visualization**	**Time difference comparison (%)**
Star spanner	1	1	0,0%	2	1	50,0%
Wrench	24	3	12,5%	3	2	66,7%
Racheting wrench	1	1	0,0%	1	1	0,0%
Possible to remove?	No	No		No	No	

In **none** of the cases examined it was possible to remove the screw – as seen by the example given on Figure 4.20.

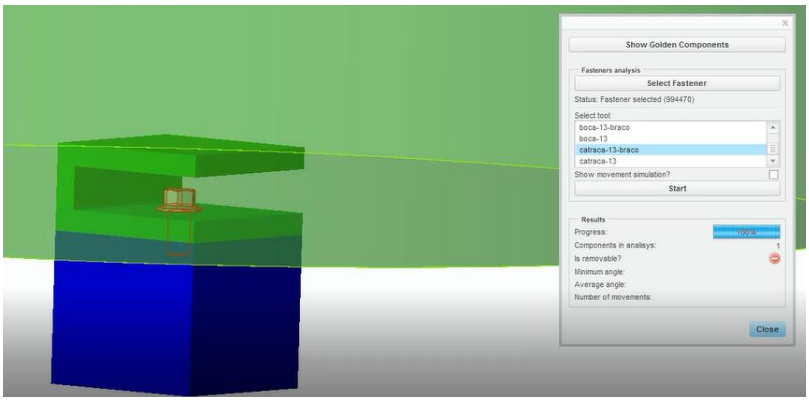


Figure 4.20 – Top barrier of 20 mm – not possible to remove fastener

As previously discussed, it was obvious that with either tools removal would not be possible. Therefore, plug-in presented the expected results. See "Video Top barrier 20 mm"[20] for further details.

With a star spanner and ratcheting wrench the plug-in returned nearly an immediate answer showing that it was not possible to remove the screw.

However, for a regular wrench there was a much greater time difference between tests with and without P95 hand. To understand this time difference Figure 4.21

[20] Available on: <https://www.youtube.com/watch?v=htnLcOhwQ5I&feature=youtu.be>. Access on: 26 Feb. 2017.

illustrates the reason. As the P95 thumb is too close to the tool end, in any angle scenario, the interference is instantly acknowledged. Therefore, leading to a much shorter time analysis when compared to the tool only.

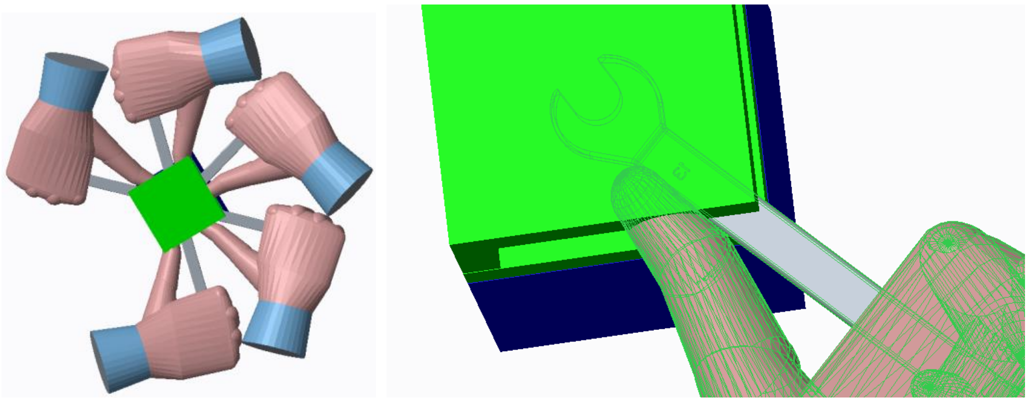


Figure 4.21 – Interference between 20mm Top Barrier and P95 hand

Assuming that similar problem would occur with other top barrier sizes whenever simulating it with a hand included, other hand positions were proposed. Figure 4.22 represented the P95 hand simulated until this point while Figure 4.23 presents a hand position with its thumb closer to the hand itself.

Figure 4.22 – Hand position – thumb opened

Figure 4.23 – Hand position - thumb closer to the hand itself

Also illustrated by the Figure 4.24, on the left side thumb is closer to the hand itself while on the right side it is closer to the tool end.

a/ Thumb closer to the hand itself

b/ Thumb closer to the tool end

Figure 4.24 – Hand position – top positions

Another issue raised with the top barrier verification was the possibility to deliver an incorrect removal conclusion. Recovering the analysis conducted on Figure 3.44, it is possible to observe that by positioning a regular wrench on the screw following the second coordinate system (MNT) there is a missing dimension that could be conclusive for a top barrier analysis – 1.68 mm (Figure 4.25).

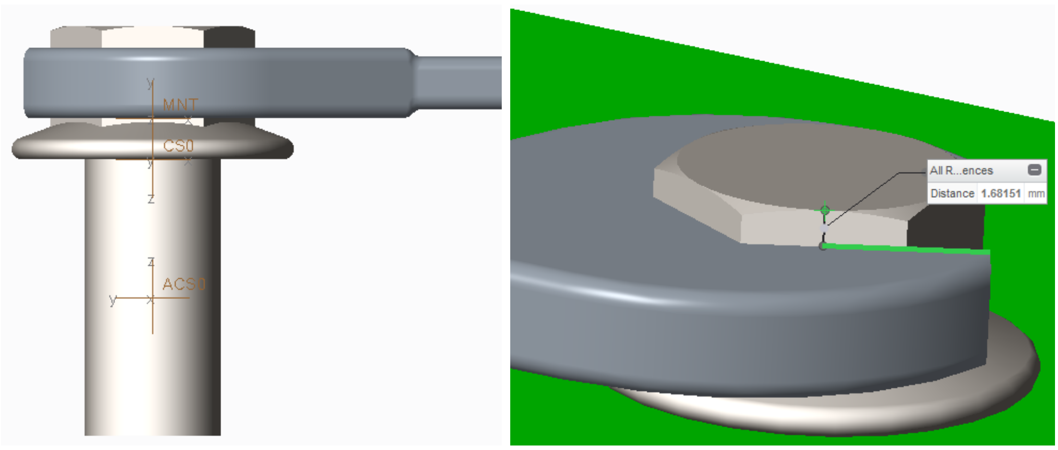


Figure 4.25 – Missing dimension on top barrier analysis

Therefore, in order to improve the analysis MNT coordinate system was moved up in "y" axis with 1.7 mm to be aligne tool and fastener surface (as presented on Figure 4.26).

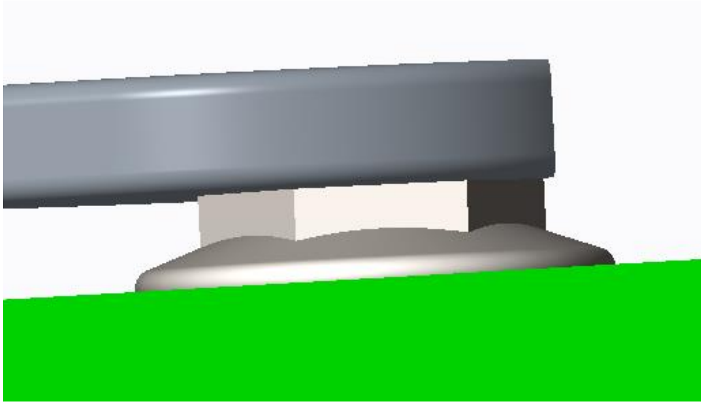


Figure 4.26 – Moving "MNT" coordinate system position higher 1.7 mm

The improvements mentioned above, hand position and tool position in relation to the fastener head, were included in the plug-in. As the simulated fastener has a total length greater than 20 mm (see Figure 3.45), these enhancements are presented in the following section with a top barrier of 40 mm instead.

4.1.3.2. Top Barrier – 40 mm

Moving to 40 mm top barrier verification and validation, Table 4.4 presents the results obtained (using the P95 hand with the thumb closer to the tool end):

Table 4.4 – Top barrier with 40 mm - using the P95 hand with the thumb closer to the tool end

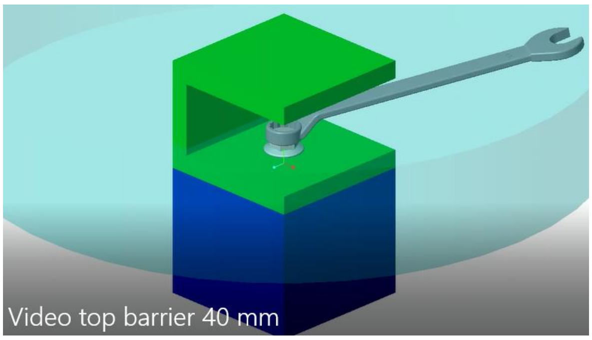
	Time stamp (seconds)							
Tool type	With Visualization	Without Visualization	Time difference comparison (%)	Possible to remove?	P95 Hand With Visualization	P95 Hand Without Visualization	Time difference comparison (%)	Possible to remove?
Star spanner	43	10	23,3%	No	10	6	60,0%	No
Wrench	39	6	15,4%	Yes	66	38	57,6%	No
Racheting wrench	1	1	0,0%	No	1	1	0,0%	No

"Video Top barrier 40 mm"[21] shows the complete simulation performed with this barrier. As earlier explained, it was expected that only with a regular wrench the fastener could be removed on this scenario. This was confirmed with the tool analysis

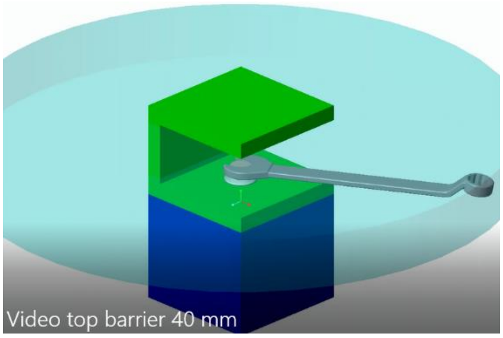
[21] Available on: <https://www.youtube.com/watch?v=9-VxhnWIbo4&feature=youtu.be>. Access on: 27 Feb. 2017.

only, but with a P95 hand included, the fastener was not possible to be removed due to the same reason of thumb being too close to the tool end.

Further evaluating this barrier, Figure 4.27 illustrates the reason why it is possible to remove the fastener with a regular wrench and **not** with star spanner. The wrench has a straight shape while the star spanner has an angle starting from the screw that unables it to remove the fastener in the end.



a/ Star spanner analysis

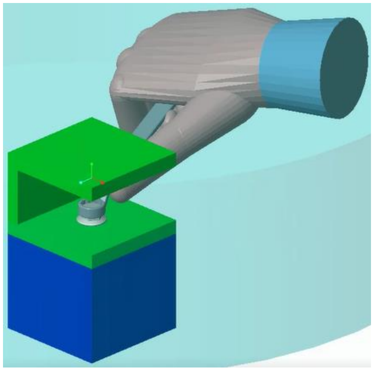


b/ Regular wrench analysis

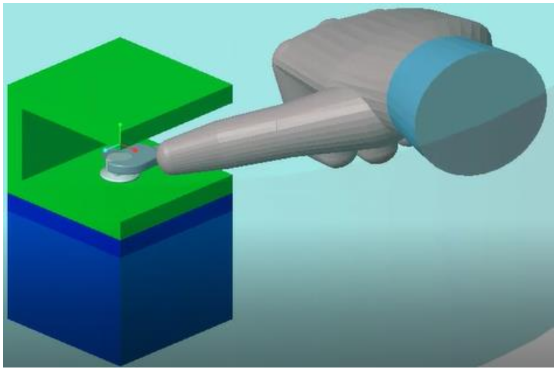
Figure 4.27 – Top barrier with 40 mm Star spanner versus regular wrench

For ratcheting wrench it was clear enough that there is no space at all to use this tool in this context.

Exploring in the analysis with a P95 hand included, the thumb position has direct influence on the regular wrench final negative result (Figure 4.28 b).



a/ Star spanner analysis



b/ Regular wrench analysis

Figure 4.28 – Top barrier with 40 mm Star spanner versus regular wrench – P95 hand included

From a plug-in perspective for both, star spanner and wrench (P95 hand included), it was not possible to remove the fasteners. This would indicate to the engineer performing the analysis that the maintainability space left for the fastener removal was not appropriate. However in a real evaluation it would probably be possible to be removed.

If in the two situations presented on Figure 4.28, P95 hand and tools would just be used to break the screw torque (like is illustrated by Figure 4.29 – from video[22]). After that, the mechanic would unscrew the fastener with his/her hand only, it would be for sure possible to remove a 29.7 mm screw total length in a 40 mm top barrier.

a/ Fastener removal start position

b/ Breaking the fastener torque

Figure 4.29 – Breaking the screw torque

Nevertheless, it is important that the engineer handling the plug-in analysis comprehends that the poor space left for the fastener removal will have high impact on the time needed to remove the screw in the end.

Another important point to be raised is that from a virtual analysis perspective, there is no simulation on rust that comes with time, making it harder to unscrew a fastener without a tool for example. Therefore, it would be highly recommended to rework the design if a removal with the desired tools is not achieved.

To improve this analysis another virtual hand was created following the guideline from Figure 4.23 – thumb closer to the hand itself – see result on Figure 4.30. Table 4.5 presents the results from the new proposed hand. Now with a regular wrench it

[22] Available on: <https://www.youtube.com/watch?v=RZmBYFaQV2w&feature=youtu.be>. Access on: 27 Feb. 2017.

was possible to remove the screw with a 40 mm top barrier, result not achieved by the star spanner and ratcheting wrench.

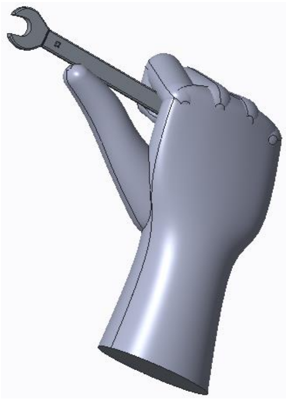


Figure 4.30 – Virtual P95 hand with thumb closer to the hand itself

Table 4.5 – Top barrier with 40 mm with thumb closer to the hand itself

	Time stamp (seconds)			
Tool type	**P95 Hand With Visualization**	**P95 Hand Without Visualization**	**Time difference comparison (%)**	**Possible to remove?**
Star spanner	52	26	50,0%	No
Wrench	58	35	60,3%	Yes
Racheting wrench	1	1	0,0%	No

"Video Top barrier 40 mm 2"[23] shows the complete simulation performed with this barrier with hand format proposed on Figure 4.30.

To enhance the simulation another hand position was also proposed – see Figure 4.31.

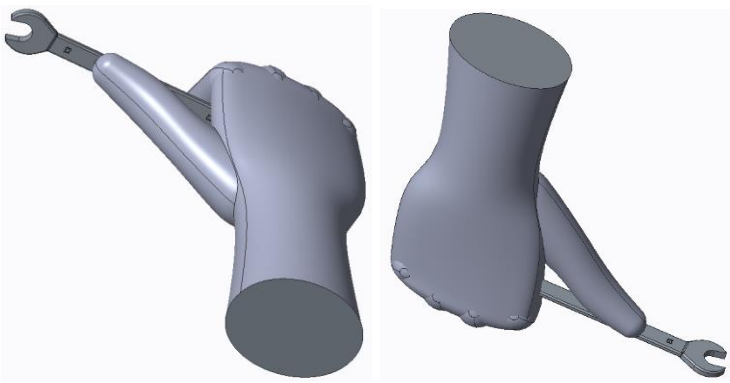


Figure 4.31 – Virtual P95 hand with thumb closer – top position

[23] Available on: <https://www.youtube.com/watch?v=dOcrat-mRG4&feature=youtu.be>. Access on: 08 Apr. 2017.

A simulation may be seen on "Video with hand on top position"[24] and Figure 4.32. The top position hand represents another ergonomic position possibility to be evaluated whenever performing maintainability analysis.

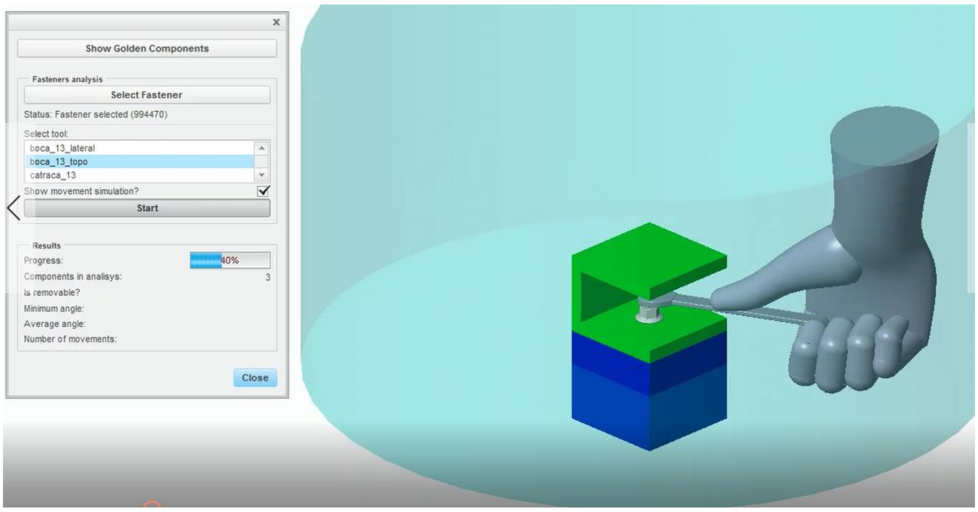


Figure 4.32 – Virtual P95 hand with thumb closer using the plug-in

4.1.3.3. Top Barrier – 90 mm

With 90 mm top barrier the results achieved are expressed on Table 4.6.

Table 4.6 – Top barrier with 90 mm

	Time stamp (seconds)							
Tool type	**With Visualization**	**Without Visualization**	**Time difference comparison (%)**	**Possible to remove?**	**P95 Hand With Visualization**	**P95 Hand Without Visualization**	**Time difference comparison (%)**	**Possible to remove?**
Star spanner	40	6	15,0%	Yes	44	13	29,5%	Yes
Wrench	37	5	13,5%	Yes	53	27	50,9%	Yes
Racheting wrench	39	5	12,8%	Yes	40	8	20,0%	Yes

"Video top barrier 90 mm"[25] was a record of all actions taken while testing such obstacle with the plug-in. Figure 4.33 shows different moments from the 90 mm top barrier analysis with a P95 hand with the thumb closer to the tool end (star spanner, regular wrench and ratcheting wrench). With all presented scenarios in all of them the fastener was removed with no trouble.

[24] Available on: <https://www.youtube.com/watch?v=XAjschrDROs&feature=youtu.be>. Access on: 08 Apr. 2017.
[25] Available on: <https://www.youtube.com/watch?v=HR_xd3mPvrM&feature=youtu.be>. Access on: 27 Feb. 2017.

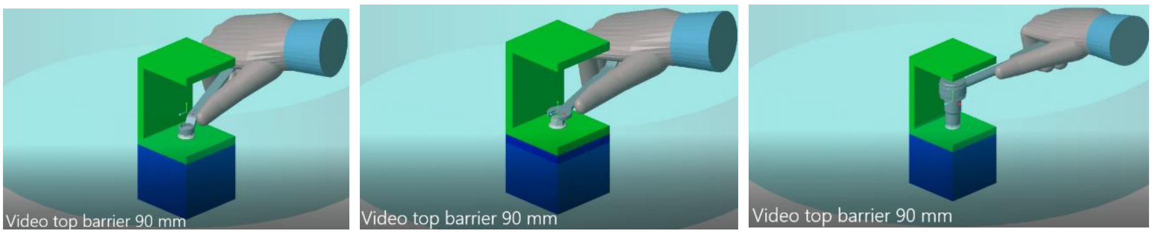


Figure 4.33 – Top barrier with 90 mm

4.1.4 Removal barriers – other verifications and validations

Other simulations were performed in order to test additional functionalities embedded in the plug-in.

4.1.4.1. Delta angle verification

For the delta angle verification a test-case with star spanner was performed with different angle selections: 10º, 1º and 30º. Results achieved are presented on Table 4.7.

As expected, the smaller the angle selected, more precise the result was but the time to process the analysis was much greater. Comparing 1° and 10° time differed approx. ten times.

Another interesting test was to add 60° or 90º as delta angles. Plug-in does accept any delta angles greater than 30°. Therefore, both analyses were executed with a 30° delta angle instead. This functionality is to avoid users from selecting too high delta angle values which would lead to a complete unreliable analysis.

Table 4.7 – Delta angle

Delta angle	Time stamp (s)	Average angle	Nº of movements
10°	43	140°	52
1°	426	149°	49
30°	14	120°	61

"Video Delta Angle"[26] shows the entire delta angles tests. Figure 4.34 shows the test results collected from the actual video.

[26] Available on: <https://www.youtube.com/watch?v=C0ykKdHoJyQ&feature=youtu.be>. Access on: 28 Feb. 2017.

Figure 4.34 – Delta angle – test results

4.1.4.2. Acceptable angle

On section 3.5.2.2 the acceptable angle selected by collecting data from Mechanics was either 60º or 75° (average of 74º). Until this point of the verification section, only 60° acceptable angle had been selected. In other words, in any trial if average angle was greater than 60º (which was the case in all test scenarios with the possibility of the screw removal) component would be highlighted with a green surrounding colour indicating a good maintainability space.

Knowing in forehand that by using a star spanner with a delta angle of 10º (Figure 4.34) led to an average angle of 140°, a test with an acceptable angle of 150° was submitted. As expected, as the value found as average angle (140°) was lower than the configured value, plug-in presented the screw with a yellow highlighting colour showing that the fastener was possible to be removed but with a lower value than normally accepted by the mechanics. See "Video Acceptable Angle" [27] and Figure 4.35 for further details.

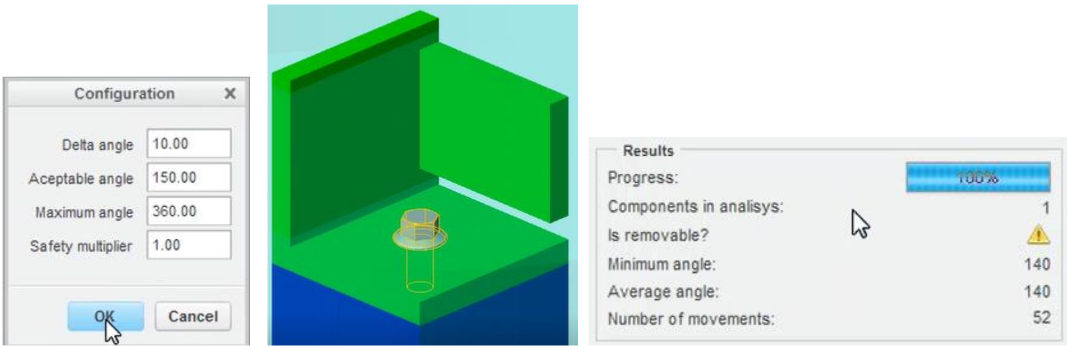


Figure 4.35 – Acceptable angle try-out images

[27] Available on: <https://www.youtube.com/watch?v=7ShwOOnrvXw&feature=youtu.be>. Access on: 28 Feb. 2017.

4.1.4.3. Maximum angle

On section 3.5.2.2 it was explained that the "maximum angle" of actuation when removing a fastener was defined as 90º or 120° on the mechanics' survey (average of 96°).

"Video Maximum angle" [28] shows two different scenarios evaluated, one with maximum angle defined as 360º and another with 90° (both using 1° as delta angle).

With 360º, using an angle constraint as test model, plug-in delivered an average angle of 140º (the real space available when using a star spanner) with just 52 movements in order to remove the fastener (Figure 4.36). Further evaluating the angle and movements analysis:

a. With a 1 mm screw thread and considering a total length of 20 mm;

b. Angle available as 140º;

c. To run 1 mm of the screw thread it is necessary 360º;

d. Therefore, 2.57 movements of 140º are necessary to run every 1 mm from the fastener thread. In total, 51.4 movements are necessary to complete the screw removal. Plug-in returned 52 as the system has a rounding-up procedure from C programming language.

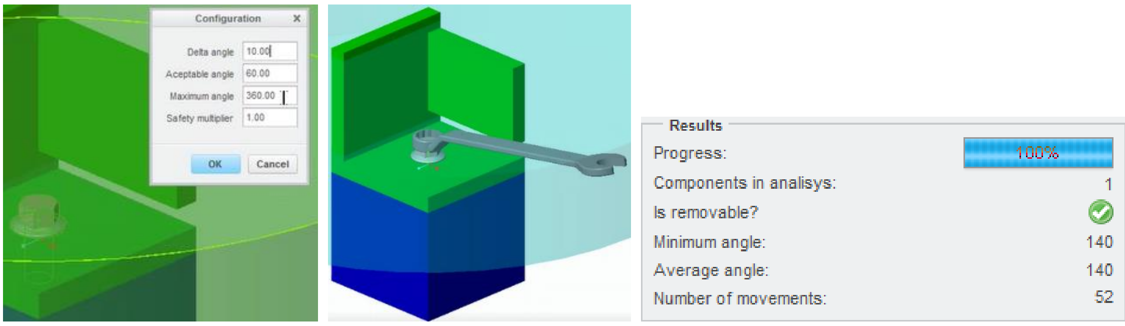


Figure 4.36 – 360° Maximum angle selected

Reducing the maximum angle to 90º, plug-in in fact prompted 90° as the average angle, and even though there was 140º as free angle space for maintenance action

[28] Available on: <https://www.youtube.com/watch?v=YmI0viFZ1QY&feature=youtu.be>. Access on: 28 Feb. 2017.

the system only considered 90º in order to calculate the number of necessary movements (number of movements increased from 52 to 80 - Figure 4.37).

In 360º to run 1 mm thread, there will be 4 movements of 90º. Therefore 80 movements would be necessary to completely remove the fastener. Plug-in returned exactly 80 movements.

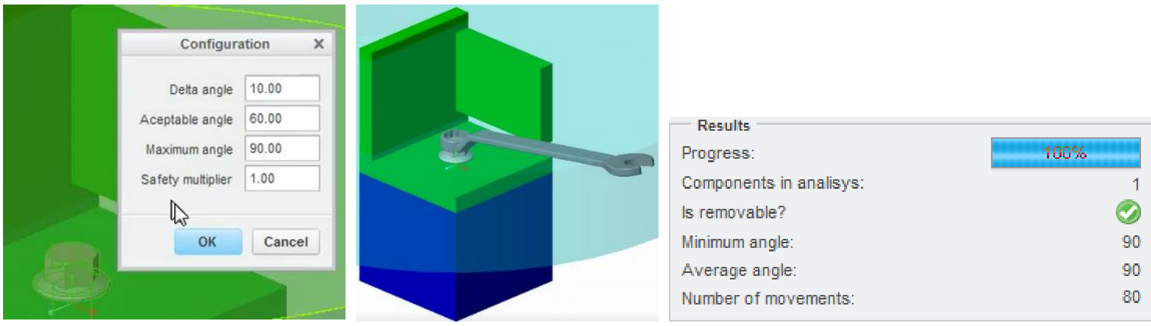


Figure 4.37 – 90° Maximum angle selected

4.2 Illustrative example from the literature

Recovering the drawing proposed from Popescu and Iacob (2013) on Figure 3.25 and Figure 3.26 (and Appendix F for details) it should be not possible to remove C1 by unscrewing F1 while C2 would still be mounted.

Using Figure 4.38 as a reference it is possible to conclude that a 29.7 mm fastener will never be removed with a 20 mm gap between C1 and C2.

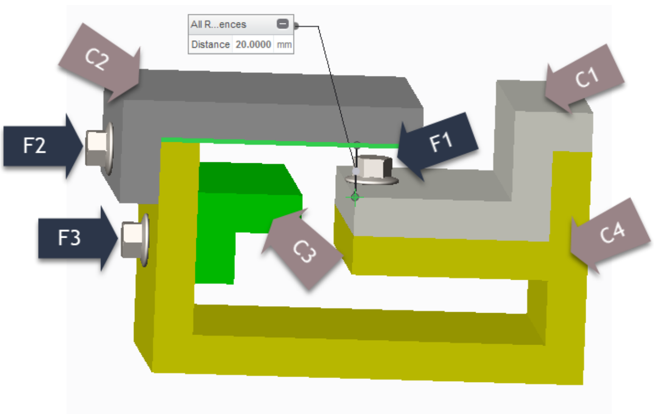


Figure 4.38 – Verification and validation model – components definition

A simulation was performed using a regular wrench with a P95 hand to confirm this statement. Automatically the plug-in returned the screw in a red colour confirming the unfeasibility to be removed (hand with thumb closer to the tool end) – see Figure 4.39.

Figure 4.39 – Illustrative example – not possible to remove with P95 hand

Another attempt was performed with the tool only (Figure 4.40). Even though it was a longer time to present the final result, the plug-in also displayed the impossibility to remove the fastener - Figure 4.41 (see "Video Illustrative example" [29]).

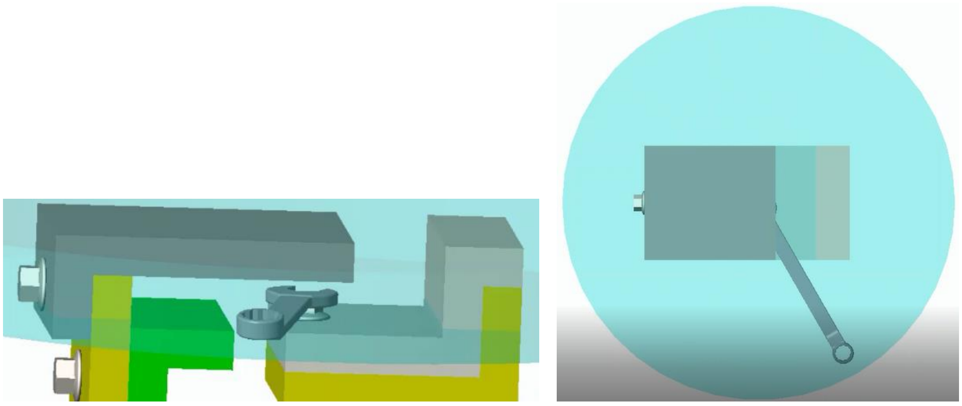


Figure 4.40 – Illustrative example – try-out with wrench only

Rather than repeating the sequence proposed by Popescu and Iacob (2013), a new simulation was performed using a P95 hand with a regular wrench with the following sequence:

[29] Available on: <https://www.youtube.com/watch?v=wN-YC99yTbs&feature=youtu.be>. Access on: 28 Feb. 2017.

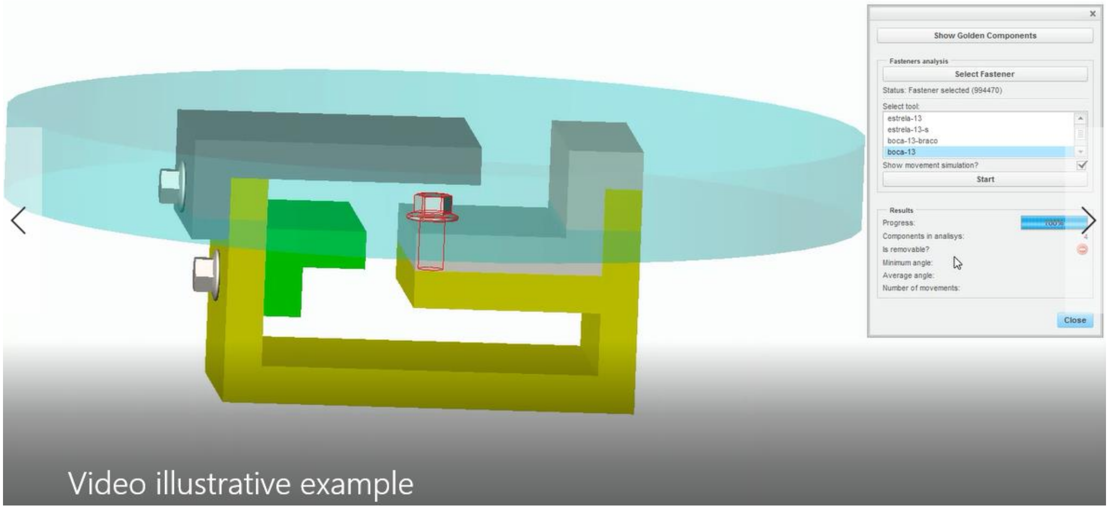
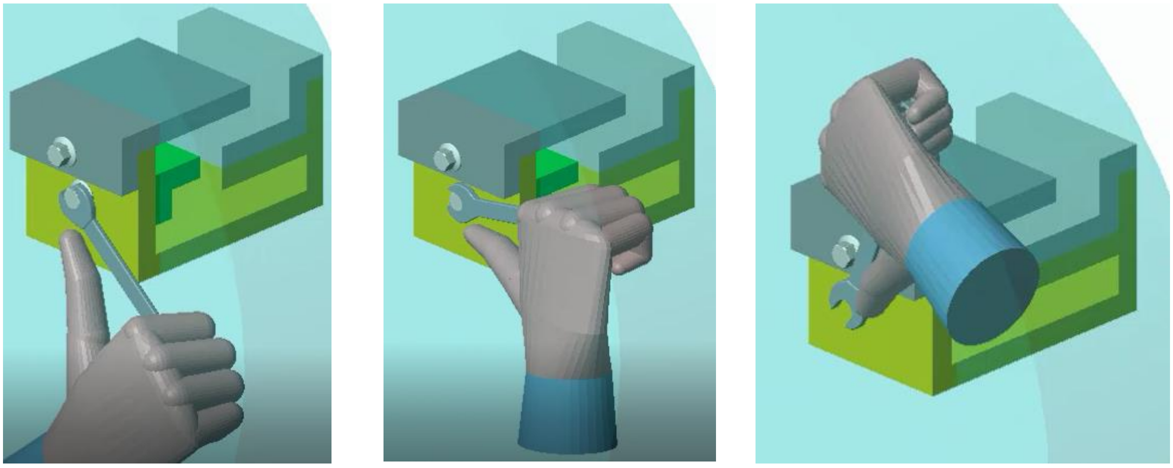


Figure 4.41 – Illustrative example – not possible to remove without P95 hand

1. Unscrewed F3 and dismounted C3 (in this scenario an angle constraint against C2 and F2 would be expected) - Figure 4.42;
2. Unscrewed F2 and dismounted C2 (360º free angle available) - Figure 4.43;
3. Finally unscrewed F1 - Figure 4.44.



a/ angle constraint - C2 b/ angle constraint – C2 c/ angle constraint – F2

Figure 4.42 – Illustrative example – Removing F3 and C3

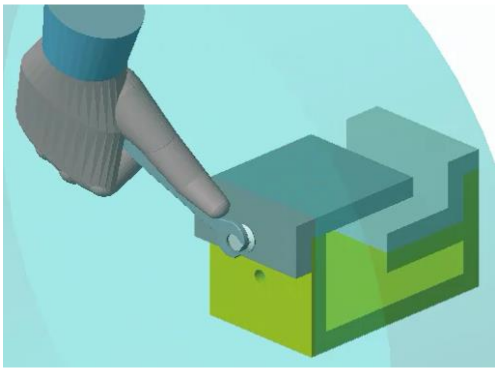
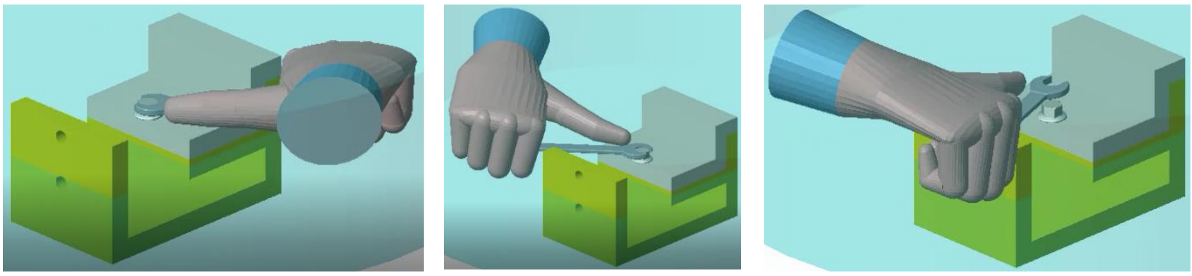


Figure 4.43 – Illustrative example – Removing F2 and C2



a/ angle constraint – C1 b/ angle constraint – C4 c/ No angle constraint

Figure 4.44 – Illustrative example – Removing F1 and C1

In all three steps above the plug-in performed all necessary analysis comprehending the available maintenance spaces. All steps above are presented in the "Video illustrative example dismounting procedure" [30].

4.2.1 Testing golden components functionality

C3 part was named "TB89056_MODELO_C3.PRT" in the PTC Creo assembly file - Figure 4.45.

Supposing that such part would be considered as a golden component, its nomenclature was updated in the plug-in database - Figure 4.46.

Back to the plug-in, Figure 4.47 shows how the original status for C3 part was.

After pressing "Show Golden Components" C3 part was presented with the intended highlight on PTC Creo - Figure 4.48, confirming the correct functionality of

[30] Available on: <https://www.youtube.com/watch?v=eh07SIj08a8&feature=youtu.be>. Access on: 28 Feb. 2017.

the plug-in. “Video golden component” [31] shows the complete procedure described in this section.

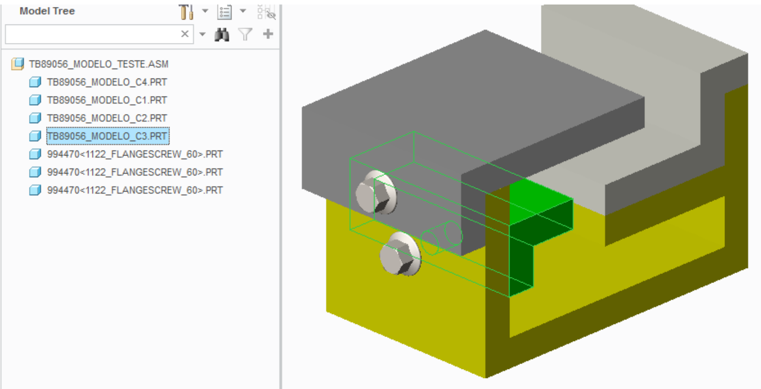


Figure 4.45 – Illustrative example – C3 part

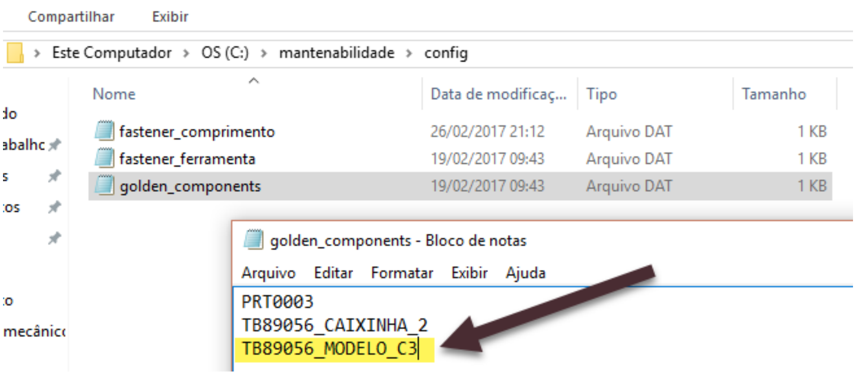


Figure 4.46 – Illustrative example – C3 part updated as golden component in the database

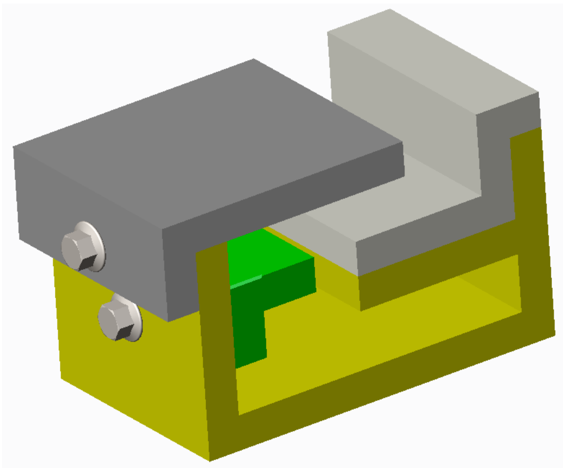


Figure 4.47 – Illustrative example – C3 part original status

[31] Available on: <https://www.youtube.com/watch?v=pnqatRhehq8&feature=youtu.be>. Access on: 28 Feb. 2017.

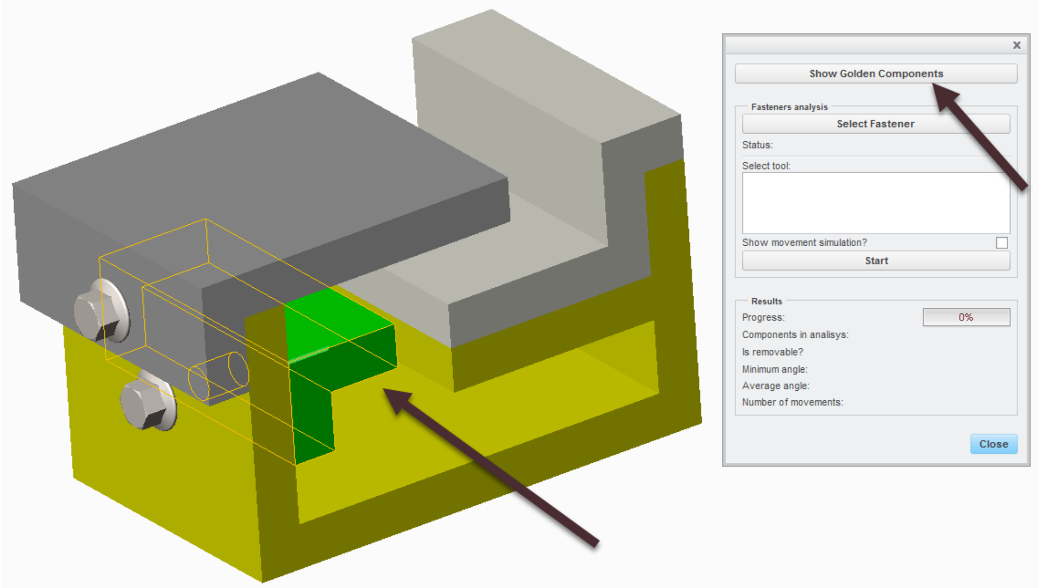


Figure 4.48 – Illustrative example – C3 part status as golden component

4.2.2 Number of components

In order to validate the number of components presented by the plug-in another test was performed using Popescu and Iacob (2013) illustrative example.

First step was to evaluate with a regular wrench the removal of F2. Plug-in presented "0" components in analysis. This in fact was confirmed by the "Interference volume analysis" as presented on Figure 4.49. Note: as earlier explained in this thesis the actual fastener under the removal analysis is not considered in the components count.

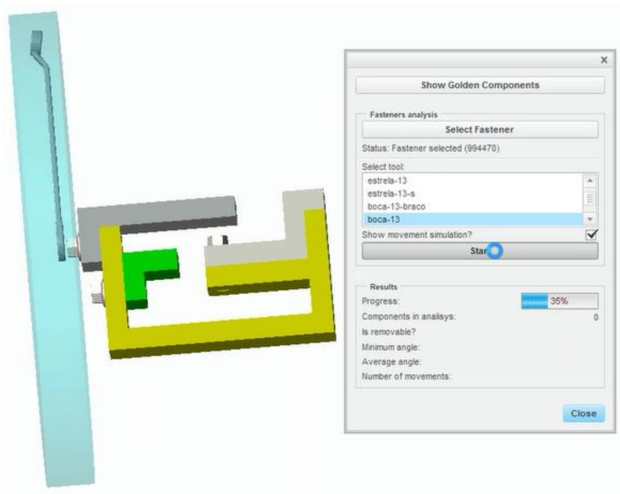


Figure 4.49 – Illustrative example – Interference volume on F2 removal

Next test performed was a P95 hand and a regular wrench still evaluating F2 screw. Plug-in returned three components in the analysis. As seen on Figure 4.50 the three components interfering with the volume are C2, C4 and F3 confirming the information provided by the simulation.

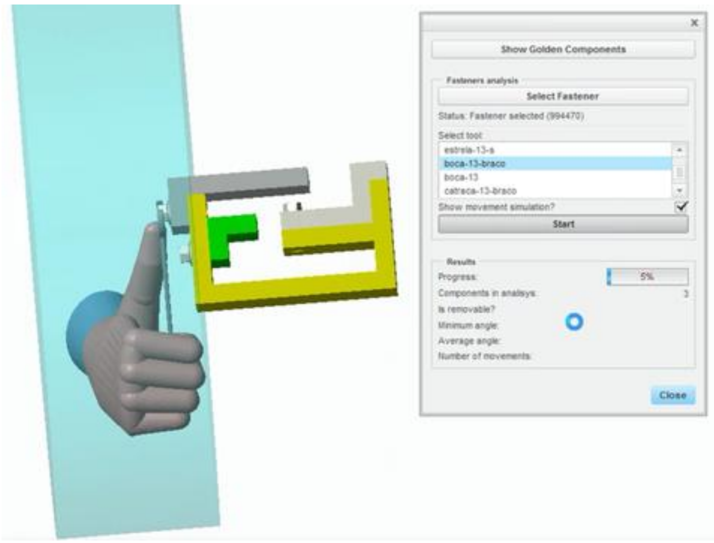


Figure 4.50 – Illustrative example – Interference volume on F2 removal with P95 hand included

New test started with a regular wrench and F3 fastener. Plug-in returned two components in the analysis. Information confirmed by Figure 4.51 as C2 and F2 are the only parts interfering with the volume.

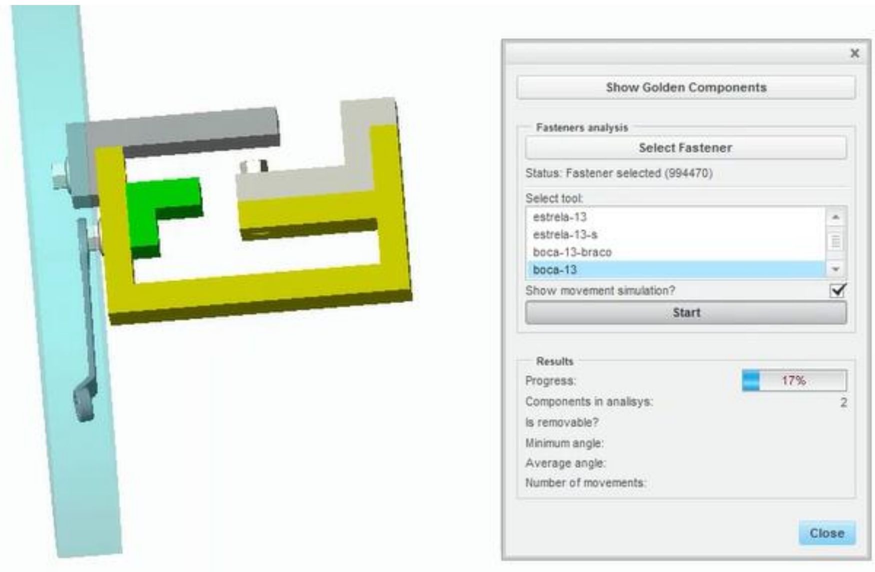


Figure 4.51 – Illustrative example – Interference volume on F3 removal

When testing the same F3 fastener but with a P95 hand included, system returned four components in analysis. When observing Figure 4.52 the interference volume analysis is in contact with C2, F2, C3 and C4.

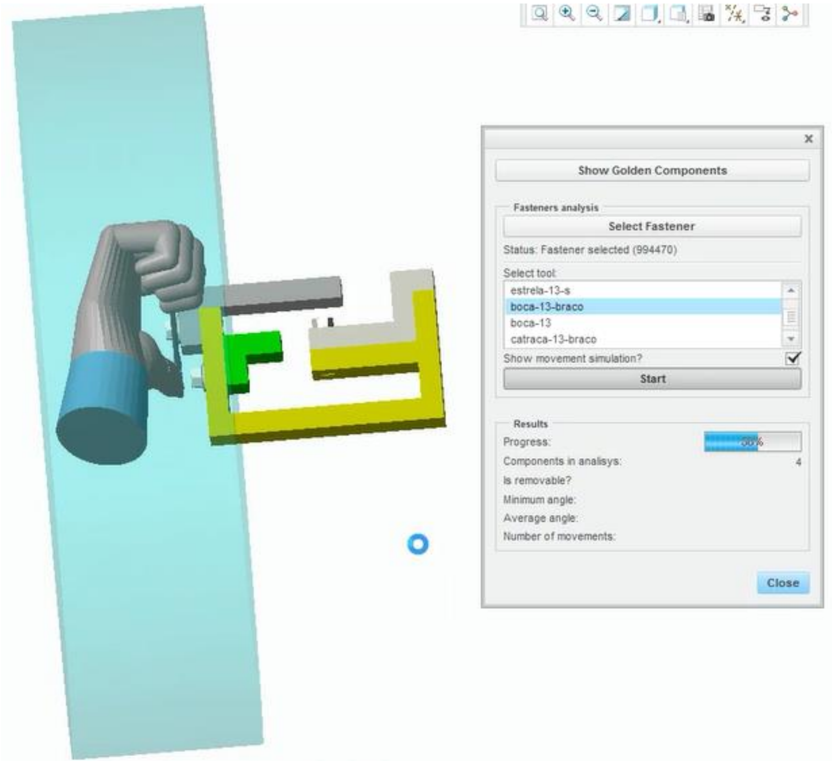


Figure 4.52 – Illustrative example – Interference volume on F3 removal with P95 hand included

On the fifth test, a regular wrench was used to simulate the removal of F1 screw. As presented on Figure 4.53 the volume is interfering with C1, C2, F2, C4 confirming the value of four components in the analysis that was presented by the plug-in.

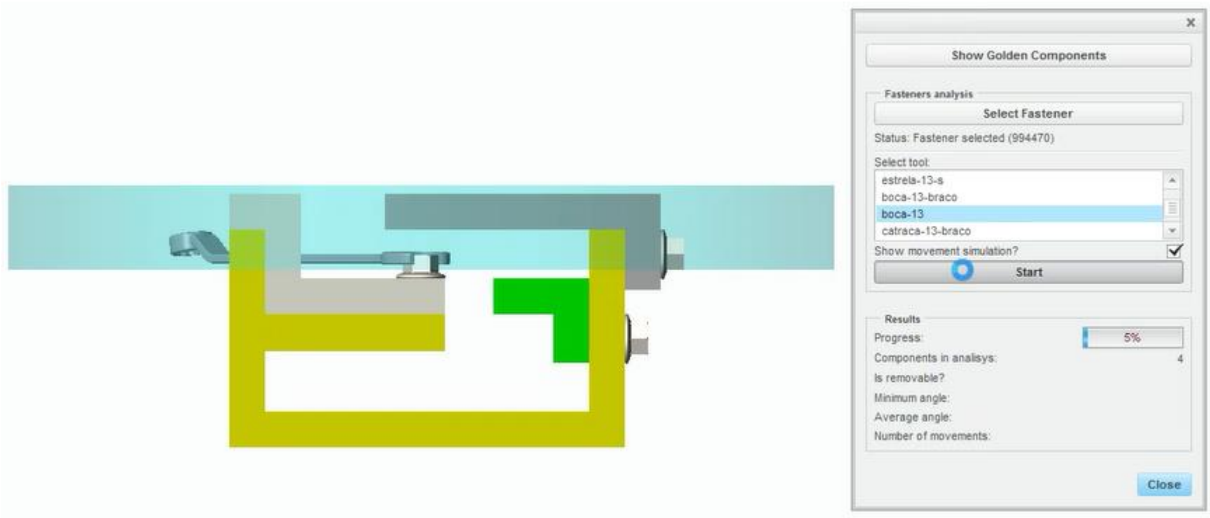


Figure 4.53 – Illustrative example – Interference volume on F1 removal (opposite view)

The last performed test on the components number validation was with a P95 hand still using F1 fastener as a reference. For this analysis, plug-in presented the highest number of components in the analysis – six components. By evaluating Figure 4.54 it is possible to conclude that the volume is interfering with C1, C2, F2, C3, F3 and C4.

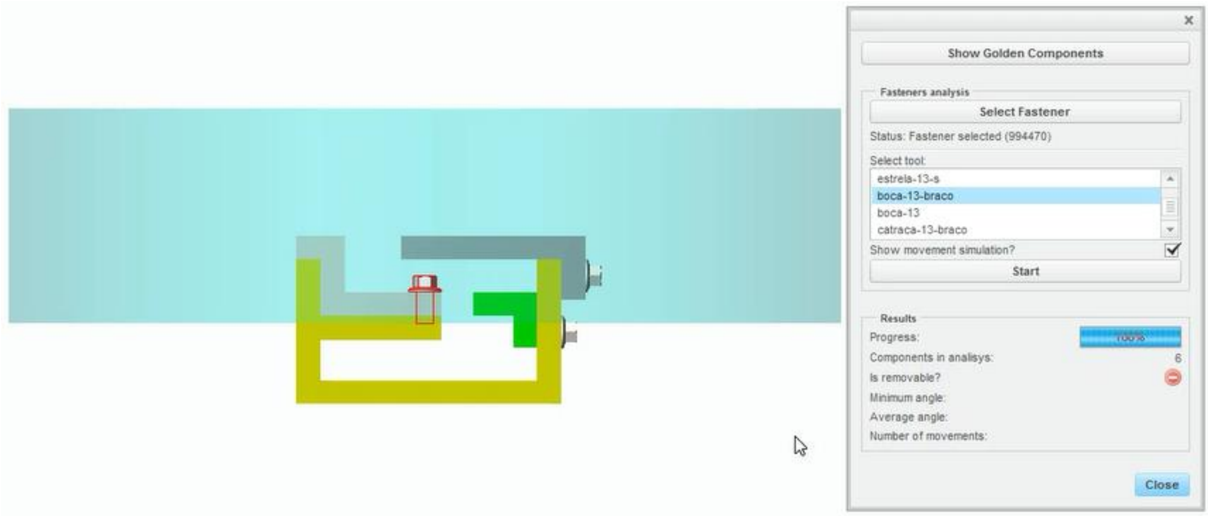


Figure 4.54 – Illustrative example – Interference volume on F1 removal with P95 hand included (opposite view)

"Video component analysis" [32] shows all the steps described in this section.

4.2.3 Safety multiplier

If a user would prefer to apply a safety factor on his/her analysis, the "safety multiplier" configuration could be changed.

Figure 4.55 presents a safety multiplier equal to 1 when using a regular wrench only.

When safety multiplier was changed to 2 the volume was changed to the Figure 4.56 **a**. And Figure 4.56 **b** was a result of a safety multiplier equals to 5.

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[32] Available on: <https://www.youtube.com/watch?v=gEjTTI7PnHI&feature=youtu.be>. Access on: 28 Feb. 2017.

For this specific illustrative example there was no real difference, but there could be other simulation scenarios that a user could apply other safety multipliers in order to broaden its analysis taking into consideration more components.

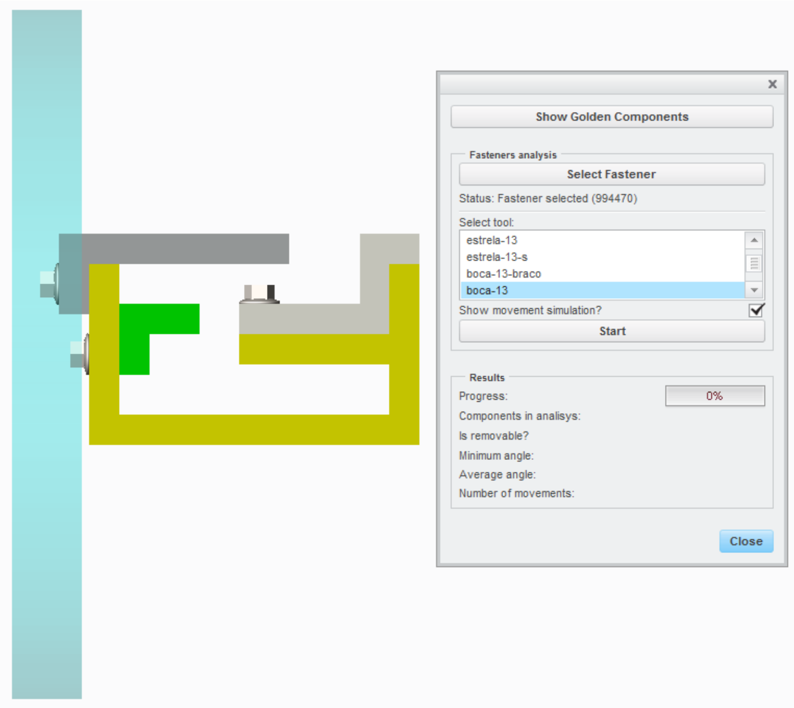
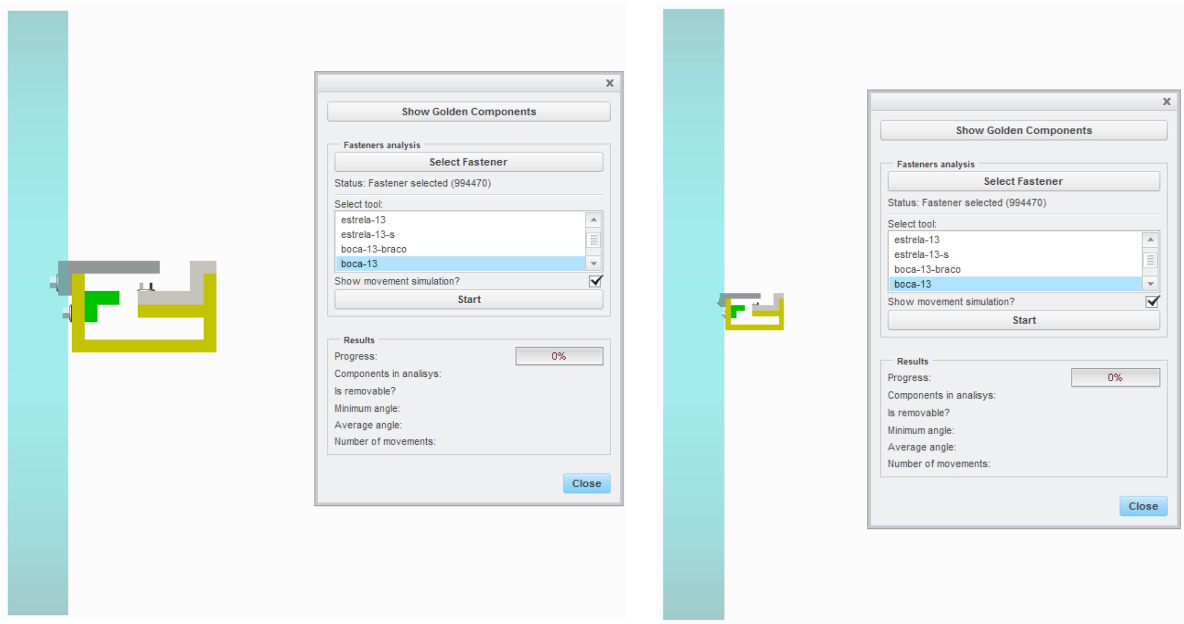


Figure 4.55 – Illustrative example – safety multiplier 1



a/ safety multiplier = 2

b/ safety multiplier = 5

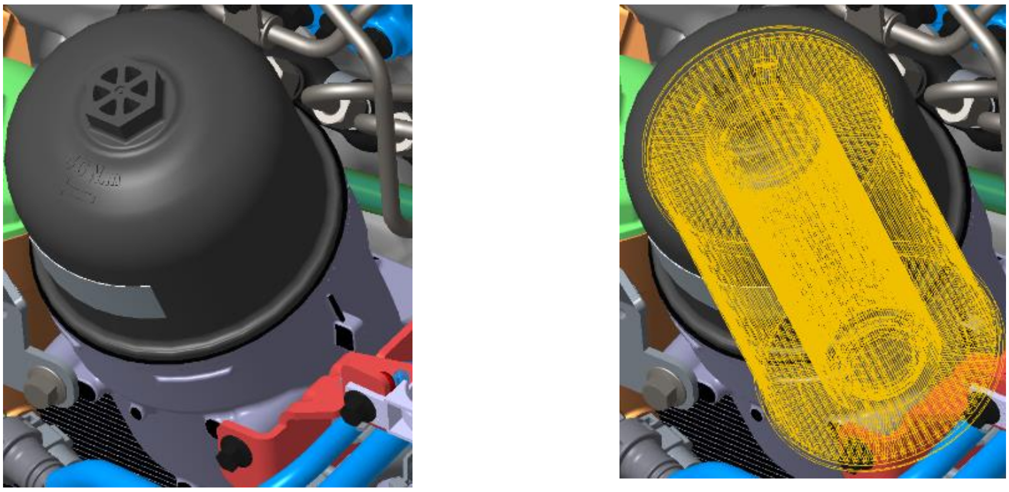
Figure 4.56 – Illustrative example – safety multiplier 2

4.3 Verification against another plug-in concept

Junior (2015) used a verification model as proposed by Figure 3.29, Figure 3.30 and Figure 3.31. As mentioned earlier, with a star spanner and a ratcheting wrench his conclusion was that it was not possible to remove the selected fastener. It was only with a regular wrench that it was possible to access such fastener and actually remove it. On this test-case, a tool number 10 is used instead of a 13.

Before running the fastener access simulation a "Show Golden Components" functionality was performed on a complete engine (with hundreds of parts). "Video Show Golden Components"[33] presents the details of a successful test performed when seeking for two golden components, filter and a valve cover.

Figure 4.58 shows a filter before (**a**) and after the plug-in golden component functionality was used (**b**). Figure 4.57 shows another example but this time with a valve cover. By using such functionality engineers may easily identify key components for the aftermarket and properly address the maintenance needs analysis for every highlighted component.



a/ Filter original status

b/ Filter after using golden component function

Figure 4.57 – Filter golden component

[33] Available on: <https://www.youtube.com/watch?v=WEbtITNUCzs&feature=youtu.be>. Access on: 05 Mar. 2017.

a/ Valve cover original status

b/ Valve cover after using golden component function

Figure 4.58 – Valve cover golden component

When running the plug-in on Junior (2015) case study several findings were registered. First test performed was an access analysis using a star spanner (Figure 4.59). Test was performed with a complete engine file (approx. 1.63 GB). Due to the file size, even though it was possible to implement such analysis, from a final user perspective it was extremely time consuming. It took around four hours to conclude the evaluation. Even if the interference volume only considered 12 components in the analysis, processing time was too high. “Video case study star spanner”[34] partially illustrates the access analysis with a video speed multiplied by eight times.

At the end of the evaluation the conclusion was that it was possible to remove the fastener with a star spanner (Figure 4.60). This differs from the conclusion from Junior (2015), once on his study a star spanner with size 13 was wrongly selected.

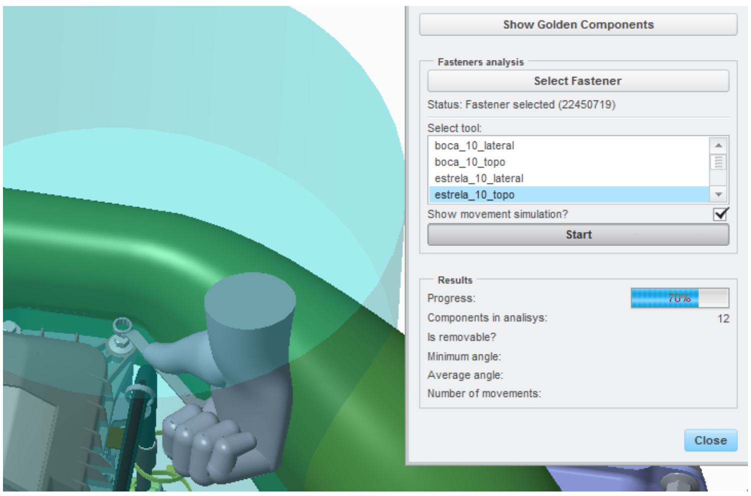


Figure 4.59 – Valve cover access analysis with star spanner

[34] Available on: <https://www.youtube.com/watch?v=S8K56PUNZiY&feature=youtu.be>. Access on: 09 Apr. 2017.

Figure 4.60 also shows that an average angle of 32º was found after 222 movements. Fastener was converted to yellow colour as it was a lower average angle compared to the acceptable angle selected (60º). In other words, even though it was possible to be removed, fastener access solution is poor and should be enhanced by the design engineer.

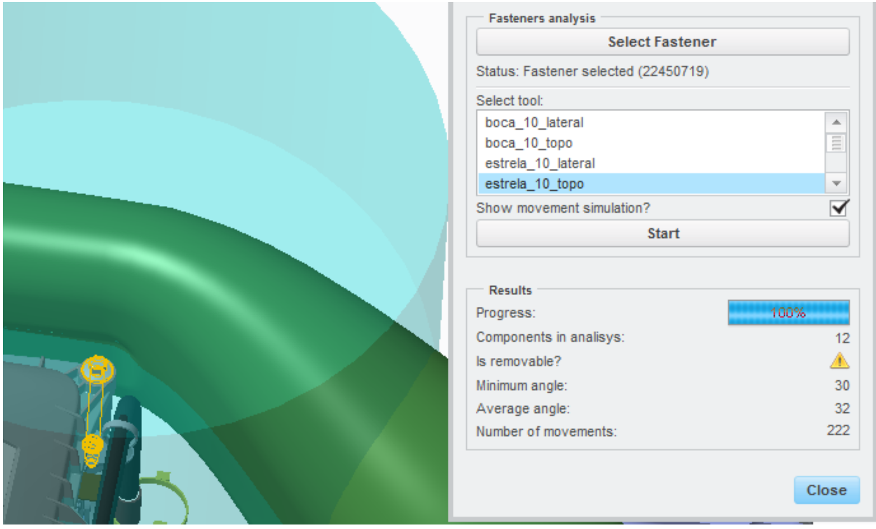


Figure 4.60 – Valve cover access analysis with star spanner - conclusion

An analysis with a regular wrench was also performed. It took around seven hours to complete the access analysis. After 360 movements with an average angle of 20º plug-in was able to deliver a result (Figure 4.61). Due to the regular wrench shape (Figure 4.62) the interference between tool and hand with the rest of the models was greater, mainly compared to the engine harness, with a total of 22 components in the analysis. This led to an extra of 3 hours in the maintainability analysis compared to the star spanner.

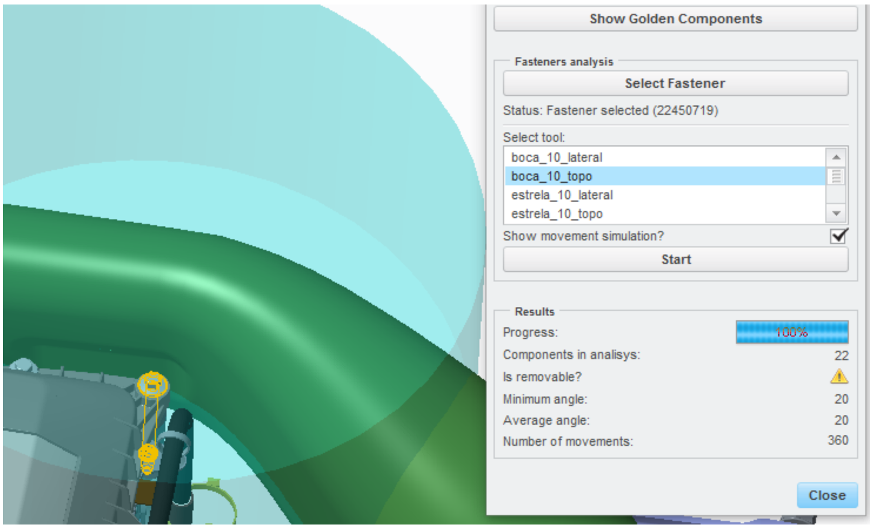


Figure 4.61 – Valve cover access analysis with regular wrench - conclusion

Figure 4.62 – Valve cover access analysis with regular wrench – two positions

Final analysis was performed with ratcheting wrench. As expected it was not possible to remove the screw (Figure 4.63). Plug-in returned this conclusion within one minute only.

Even if the time demanded to perform the analysis was extremely excessive (as presented on Table 4.8), some improvements are important to be highlighted when comparing thesis model against Junior (2015) solution:

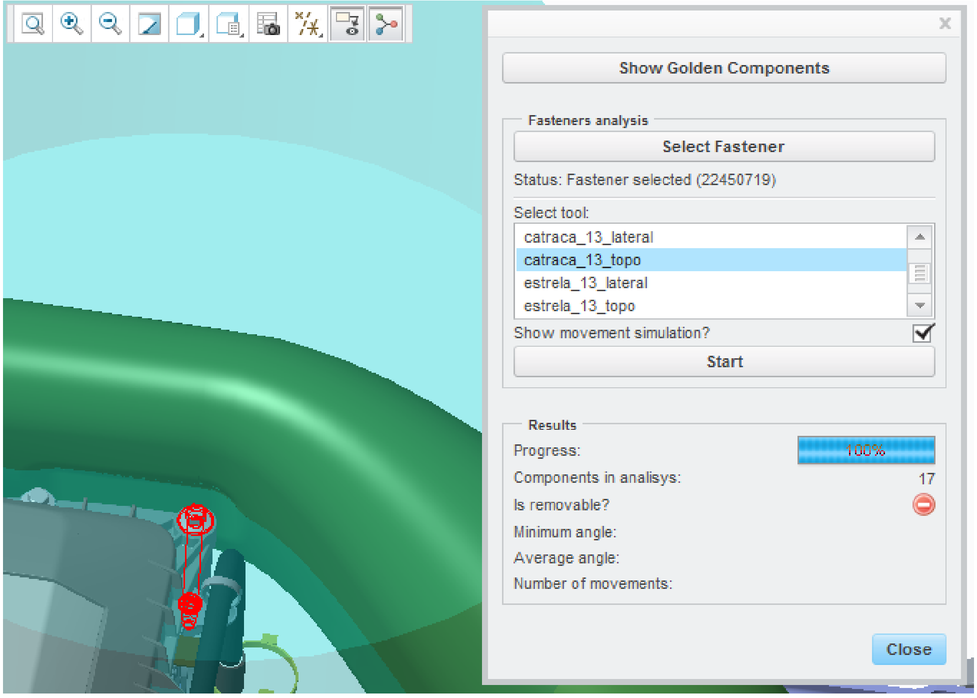


Figure 4.63 – Valve cover access analysis with ratcheting wrench – conclusion

a. Thesis model is more flexible once it needs only the screw length to start performing an access analysis (there is no need to store different swept volumes in a database);

b. Thesis plug-in covers any angle available with no predefined angle swept volumes (as proposed by JUNIOR, 2015);

c. Interference analysis is delivered by the thesis plug-in demanding no extra evaluation from the final user;

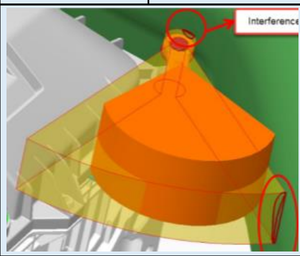
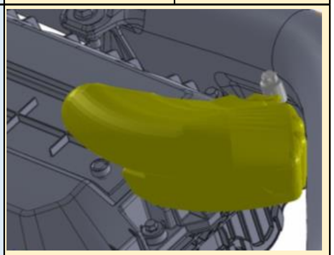
d. Thesis plug-in delivers average angle and number of movements needed to perform the fastener complete removal;

e. Based on predefined acceptable angle thesis plug-in delivers a colour result showing to the designer how good the access solution is;

f. Thesis plug-in provides golden component search functionality very welcome to define key components to be evaluated from a maintainability perspective.

The time demanded by the thesis plug-in to perform the evaluation though was considered to be so high that its usage on real life maintainability analysis would not be feasible. The interference analysis volume was not effective enough even if number of components were reduced to 12 only (complete engine had hundreds of parts).

Table 4.8 – Thesis time stamp versus Junior (2015) time results

	Time stamp (minutes)					
	Thesis plug-in	**Possible to remove?**	**Junior (2015) Manual evaluation**	**Possible to remove?**	**Junior (2015) Plug-in**	**Possible to remove?**
Tool type						
Star spanner	240	Yes	55	No	14	No
Wrench	408	Yes	55	Yes	14	Yes
Racheting wrench	1	No	N/A	No	N/A	No

Therefore, in order to improve this processing time issue, other tests were performed: i) engine with a reduced number of components analysis; ii) extrude function analysis.

An engine with reduced number of parts was tested in order to observe if gains in time would be achieved. "Video reduced number of parts" [35] registered a small sample of such test with a star spanner. Even though the maintainability analysis was faster, it still demanded too much time to be concluded – 172 minutes. Around 30% less time if compared to the complete engine analysis. Therefore, even with less components and with the aid of the interference volume, the system did not improve as much as it was expected to present a prompt result.

"Video reduced number of parts – regular wrench" [36] recorded a small portion of regular wrench test. In the same manner as with the complete engine parts result was very time consuming, around 20% less time only. Figure 4.64 presents the results achieved during the simulation. The only difference is the number of components under

[35] Available on: <https://www.youtube.com/watch?v=zCWShvUw2v0&feature=youtu.be>. Access on: 15 Apr. 2017.
[36] Available on: <https://www.youtube.com/watch?v=qXHx0FVqoLU&feature=youtu.be>. Access on: 16 Apr. 2017.

analysis – dropping from 22 (Figure 4.61) to 16 (once several engine parts were removed from the assembly).

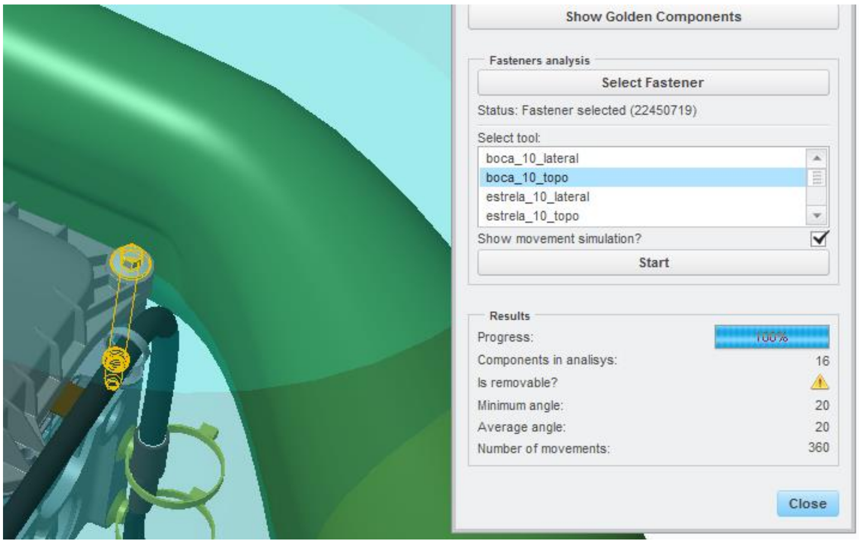


Figure 4.64 – Engine with reduced number of parts - Valve cover access analysis with regular wrench - conclusion

Another step in the investigation was performed. With the reduced number of parts an extrude action was implemented considering the aimed screw in the centre. "Video reduced number of parts + extrude" [37] was recorded showing that evaluation speed was improved. For star spanner maintainability analysis dropped to 88 minutes (approximately 65% less if compared to the original engine file). Figure 4.65 was extracted with 7% of star spanner analysis.

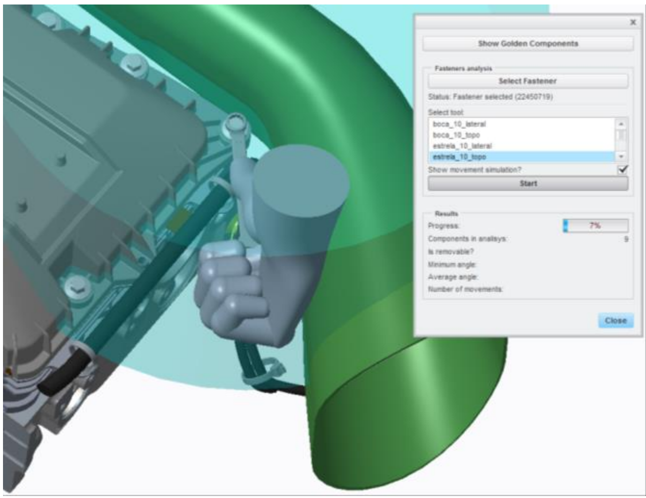


Figure 4.65 – Engine extruded - valve cover access analysis with star spanner

[37] Available on: <https://www.youtube.com/watch?v=jH5XR7Q5fVk&feature=youtu.be>. Access on: 16 Apr. 2017.

The same procedure with an extruded engine part was repeated with a regular wrench. Figure 4.66 was also extracted with 7% of analysis. “Video reduced number of parts + extrude 2” [38] was recorded and represents just part of the evaluation that in total needed 176 minutes to be completed. Even though it was still a very time consuming analysis, it represented 43% of the time if compared to the first analysis performed with the complete engine. The result was the same as presented on Figure 4.64.

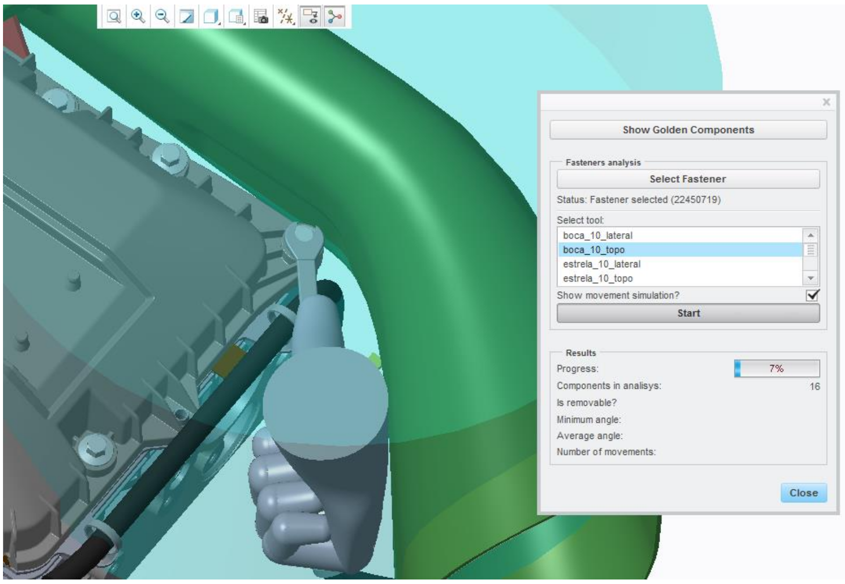


Figure 4.66 – Engine extruded - valve cover access analysis with regular wrench

Table 4.9 is a summary of all results achieved with the engine case study.

Table 4.9 – Thesis time stamp – engine case study

	Time stamp (minutes)					
	Thesis plug-in	**Possible to remove?**	**Thesis plug-in Reduced nº of parts**	**Possible to remove?**	**Thesis plug-in Extruded engine**	**Possible to remove?**
Tool type						
Star spanner	240	Yes	172	Yes	88	Yes
Wrench	408	Yes	334	Yes	176	Yes
Racheting wrench	1	No	1	No	1	No

[38] Available on: <https://www.youtube.com/watch?v=to9RvZCOr_w&feature=youtu.be>. Access on: 16 Apr. 2017.

Even though processing time improved substantially from the complete engine analysis to firstly a reduced number of parts engine and finally narrowing down the analysis to an extruded engine volume, best time reached (88 minutes) is not acceptable for real use in daily project development activities.

The important conclusion from the investigation performed and summarized on Table 4.9 is that the maintainability analysis is working, even though it was time consuming. Further development on the plug-in is necessary to improve its response. Also, further tests should be performed with different CAD systems suppliers in order to understand in which degree the internal PTC functionalities were responsible for the long lead-times measured (see section 4.4.1.2 in which regular PTC Creo Parametric users already complain about global interference function from this CAD software).

It is very important to highlight that, basically the interference volume is narrowing down the number of parts in the evaluation approach. In the engine case study, even though the number of parts were extensively reduced, from hundreds of parts to just nine or sixteen components, PTC interference analysis function used along the plug-in proposal was still very time consuming. Despite the given response time, interference volume analysis compose an breakthrough idea to reduce the scope of analysis solving one of the future issues from Moscheto (2009) – lack of a method to concentrate the analysis only in a reduced volume on a complete given CAD module.

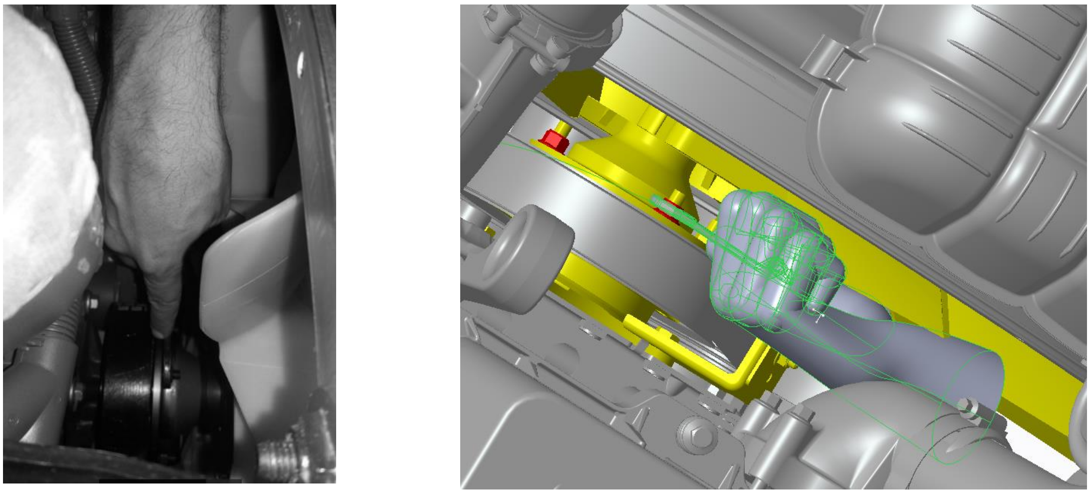
Another important fact to be raised is that a more powerful computer could have been used (see details on Appendix D) reducing even further total analysis time.

4.4 Verification and validation with engineers

As a final step on the verification and validation phase, after performing several different evaluations and confirming the model functionality, a case study had to be selected and applied with engineers with different experience levels.

Two case studies proposals were tested in both, real life and virtual environments. The idea was to find a good test-case from their normal working facilities.

First model tested was a maintainability access of an engine fan (Figure 4.67 **b**). From the start it was realized that another hand shape was missing in the plug-in in order to avoid clashing and have a match with real life test (Figure 4.67 **a**). Arm and hand needed to be aligned in order to reach a fastener in such position as given on the example of Figure 4.68. As such hand position was not available in the plug-in, this test case was not applied any further. However, it supplied good input for improvement of the plug-in for the future.



a/ Physical verification b/ Virtual verification

Figure 4.67 – Engine fan case study

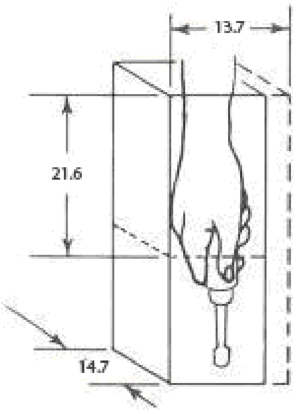


Figure 4.68 – Space required to use a screw driver (cm)
Source: Adapted from Blanchard, Verma and Peterson (1995).

Second model tested was a cab example (Figure 4.69). It was possible to evaluate the selected fastener but due to the complete CAD model size and complexity, it generated the same time delays as perceived in the Table 4.9 for the previous engine model tests. Therefore, to use it as case study with different engineers would be too time consuming hindering the plug-in analysis itself.

A simpler case study was selected to support this verification and validation phase within a smaller analysis time frame. Figure 4.70 shows the 3D module environment selected (further details available on Appendix G). The idea was to add three new screws (marked in blue on Figure 4.70 – A1, A2 and A3) in Popescu and Iacob (2013) module. Figure 4.38 C2 and C3 parts were adapted with different barriers.

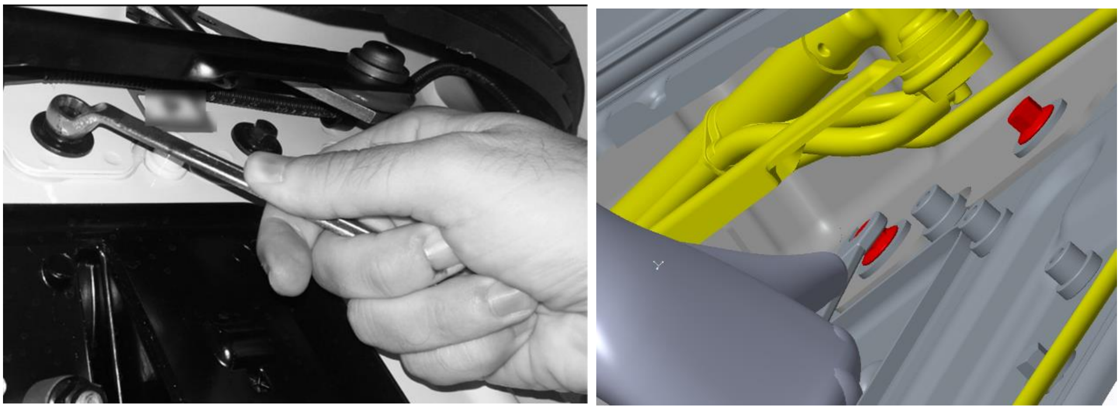


Figure 4.69 – Cab case study

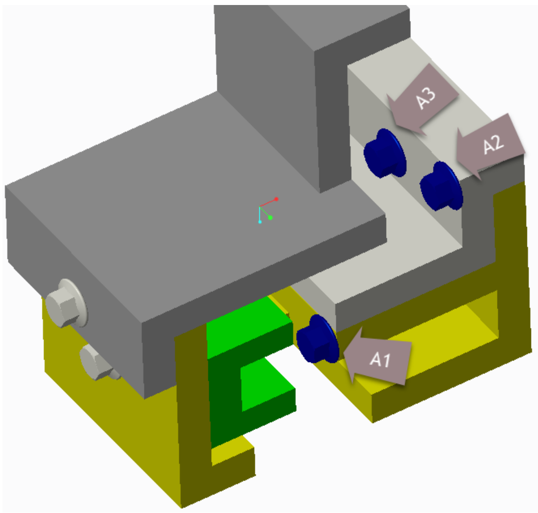


Figure 4.70 – Case study selected

This case study had the following problem on its access:

a. Fastener A1 with no enough space to be completely removed using a lateral P95 hand and a regular wrench tool (Figure 4.71);

b. Fasteners A2 and A3 with enough space to be removed (Figure 4.72) but with different access levels. A2 access level with a regular wrench and a lateral P95 hand is presented on Figure 4.73. A3 access level with a regular wrench and a lateral P95 hand is presented on Figure 4.74. “Video case study” [39] was recorded showing all maintainability analysis on this CAD module for A1, A2 and A3 fasteners.

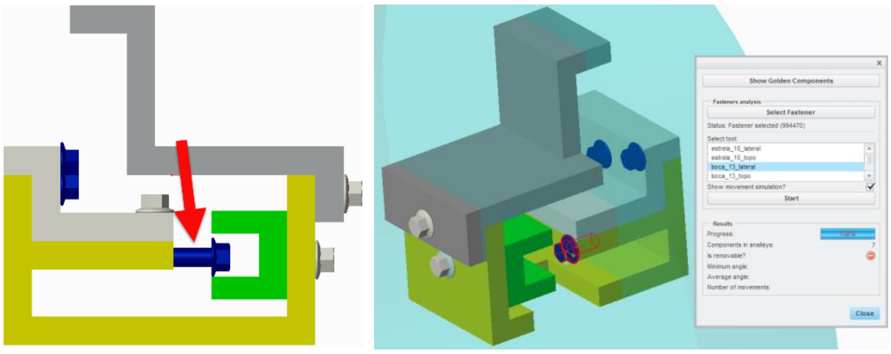


Figure 4.71 – Issue on A1 fastener

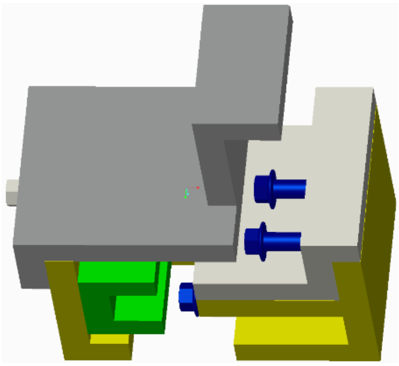


Figure 4.72 – No removal issues on A2 and A3 fasteners

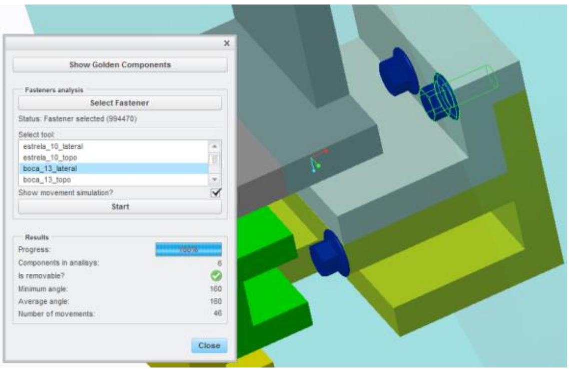


Figure 4.73 – Access on A2 fastener with regular wrench

[39] Available on: <https://www.youtube.com/watch?v=0n4pRM6h_Hs&feature=youtu.be>. Access on: 06 May 2017.

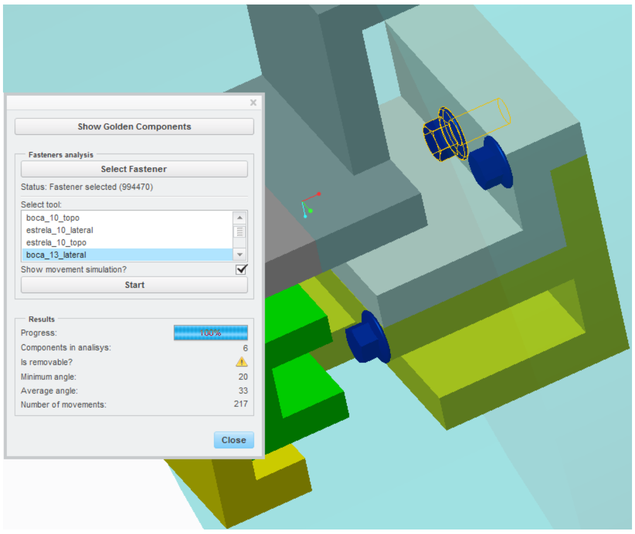


Figure 4.74 – Access on A3 fastener with regular wrench

With a test-case selected, a final verification and validation phases started with engineers with different experience levels.

The plug-in validation with the proposed case study followed the next steps:

a. Two groups of five engineers were formed with mixed experience levels;

b. A design task was prompted asking the designers to evaluate the maintainability aspects of A1, A2 and A3 fasteners (Figure 4.70). They had to use a regular wrench with P95 hand on top position (using Show Movement feature):

b.1. On the first group (Questionnaire A – Appendix E), the model presented as case study was detailed, the plug-in was briefly explained and provided to support maintainability evaluations;

b.2. On the second group (Questionnaire B - Appendix E), no extra information was supplied except for the component to be evaluated and the library with 3D universal tools (regular wrench) and a manikin P95 virtual hand. After performing their own maintainability analysis on the three screws, plug-in was presented in the exact way as for Group A. Idea was to collect further thoughts from these users as they experienced a day-to-day analysis and then present the plug-in in order to capture their feedback.

c. Feedback was collected from both groups on a written survey on the maintainability analysis using the plug-in following Appendix E.

4.4.1 Feedback collected highlights

From the ten engineers that took part on the survey the following identification details may be expressed:

a. They have in average 31.5 years of age. Younger participant with 23 and the oldest with 39 years of age. Average of Group A was 34.6 and Group B with 28 years of age;

b. They had in average 9.6 years of experience working as CAD specialists. Being the less experienced one with just two years in the position and the most experienced one with twenty years working with CAD modules. Group A with average of 11.2 years of experience and Group B with eight years;

c. From a maintenance background three have considered themselves as beginners and seven as having a reasonable experience;

d. Only one female.

4.4.1.1. Group B analysis – without plug-in support from the start

Starting with Group B analysis, which evaluated the case study from Figure 4.70 without the plug-in in the first place, the following facts can be described:

a. In average they took 11:27 minutes to conclude the analysis – lowest with 3:32 and highest with 26 minutes of analysis;

b. Just one engineer concluded that A1 was possible to be removed (incorrect answer). The same engineer wrongly concluded that A3 was not possible to be removed (the youngest designer). All other answers concluded that A1 was not possible to be removed, A2 was possible to be removed as well as A3. Three engineers commented that A3 did not have the ideal access level;

c. Two engineers found it hard to perform the maintainability analysis. One mentioned that the analysis is very depended on the designer feeling. Another complained that PTC is slower than Catia V5 Cad Software;

Basically, engineers have positioned the P95 hand and regular wrench on each fastener on the original screw position and move the hand/tool around to evaluate the access level. Except for the engineer who wrongly concluded the feasibility of two fasteners removal, all other engineers have positioned fasteners at the very end of screw removal position to once again simulate hand/tool removal movement.

The junior designer answered one of the questions raised on section 2.5.9, that a maintenance analysis might be jeopardized if an unexperienced engineer performs the evaluation.

4.4.1.2. Analysis of Group A and B with plug-in usage

With the plug-in usage, Groups A and B had the following results:

a. In average 10:17 minutes were necessary to conclude the maintainability analysis. The lowest time achieved was 7:19 minutes and the highest 17:26 minutes – all leading to the correct answers. Comparing to Group B result this time in average was 1:10 minute lower than when performing the maintainability analysis without the plug-in;

b. All analysis led to the correct answer. Engineers made the following comments on the usage of the plug-in:

b.1. The plug-in shows in a better way the difficulties along the analysis. Minimum and maximum angles give a better level of details;

b.2. Four engineers mentioned that screw A3 was very hard to be removed. One of them also doubted if the angle in the end of the analysis was big enough in order to use a regular wrench with a hexagon screw head (important issued raised which the plug-in is not able to consider);

b.3. One designer considered the plug-in much faster (his analysis came from 15:30 minutes without the plug-in to 10 minutes with the usage of the tool);

b.4. One engineer felt that it was necessary to have a function to continue the analysis and be able to exactly see where the clash happened.

When questioned if they foresee a gain on using such plug-in all of the participants answered positively. They made the following comments (some comments in English are stated here using the participant words without any text change):

1 Detailed parameters analysis. Qualitative ergonomic analysis;

2 “Much less work to perform the analysis, lower chance of error”;

3 The tool gave an enormous time gain giving a guaranteed answer if the screw removal was feasible or not. Comparing to the earlier analysis (engineer belonged to Group B) the engineer wouldn't have this answer, it was something that the engineer had the feeling but no certainty about;

4 Beyond the possibility to visualize the access limitation, one can also verify the possibility to avoid unnecessary component modifications;

5 "I foresee a great business case opportunity. When using this plug-in against physical tests";

6 Possible to be used on the Project conceptual phase;

7 "To be used where there are doubts only";

8 Significant gains for designers on the early conceptual product phase;

9 "The main point is only the needed processing time. Maybe a more powerful computer could give a better perception of the processing time";

10 "Better precision and more user friendly".

Besides of being accepted as a gain for the whole product development, the plug-in was also recognized as an important tool for conceptual phase of the project, a way to reduce the level of errors and better visualize the access level.

When questioned if they would use such plug-in if it was to be available in their daily usage nine of ten participants answered that they would use it. Following comments were given:

1 It is a practical tool, which removes part of the designer responsibility to evaluate the fastener removal;

2 I judge this tool as an excellent plug-in to speed-up the development process;

3 "Plug-in not yet optimized. Too long time to perform more complex analysis" (the only designer who answered that wouldn't use the plug-in);

4 Library of tools should be totally available;

5 "Depending on the processing time. Probably could be used as a good reference to define the space claim for tooling and for daily work I would use the space claim";

6 “The only problem would be the time, with a lot of components it would be very high”.

Two participants commented after completing the questionnaire that when performing clash analysis in PTC Creo Parametric they never use its global interference function, as it is very time consuming. These feedbacks were an important connection to the time issues observed during the plug-in verification and validation phase (sections 4.3 and 4.4).

In summary, a positive feedback was given by the participants. One of the proposed ideas is not to only supply the plug-in, but also to make available a complete set of universal tools as the designer could easily access them just like a regular tool board in a workshop. Some of the answers given are directly related to the limitation of the current plug-in as just few tools are available for usage. As described earlier in this thesis, such tools were selected just as case studies. There was no aim to supply a broader offer of tools / fasteners to be tested on.

4.4.1.3. Feedback from golden components analysis

Moving to the answers about Golden Components all participants found the concept/function valid. The following comments were given about this functionality:

a. As a designer hardly this type of filter is offered for components;

b. “Priorization of what to analyse is very useful”;

c. To relate Golden components with space claims;

d. “Yes since the list is updated, big risk of information out of date due to project evolution”;

e. “I'm not sure how to include this point in current process. What would be the trigger for the designer to act using the tool?”;

f. “Easier to find core components for maintainability”.

The participants in summary accepted the concept of golden components functionality. Anyhow, it is very important to create a strong connection with product development process and decide when to use such a tool. Another topic raised was the importance to keep the list of nomenclatures and/or Part numbers constantly updated as the product evolves.

It was interesting to receive feedback about the suggestion to create a connection between Golden Components and Space Claims[40] (see Figure 2.43, Figure 2.44 and Figure 2.45 for space claims). In the participants opinion Golden Components could be a trigger to warn a designer that a space claim would be available. This connection could be a future development enhancement proposal.

In the last question of the survey all designers answered that it was easy to find highlighted components (Golden Components).

[40] All participants are nowadays using the space claims' process proposal suggested by Moscheto (2009) in their project activities in an Automotive Industry.

5 CONCLUSIONS AND FUTURE WORK

5.1 Overview

During the literature review it was possible to recognize that classical literature is barely discussing the maintainability parameter in the virtual environment during PDP. Focus is more concerned on maintainability metrics but with no real guidelines on how to actually achieve these objectives by working on project within a CAD environment.

On the other hand, new studies, usually, are either employing impracticable (yet) mathematical algorithms or 3D CAD systems maintainability analysis (on an immersive or non-immersive approach). The problem, with the studied methods though, is their high dependency on maintenance specialists in order to perform truthful evaluations.

Moscheto (2009) proposed a maintainability model and the application of a plug-in with some functionalities in PTC Creo Parametric trying to overcome the experience dependency. One fastener function was a proposal aiming to simplify and standardize fasteners selection on the 3D product concept. The drawback from this proposition though was the lack of fastener accessibility consideration.

Therefore, considering the literature review and the drawback from earlier plug-in, one important question/gap was raised along Chapter 2: could a model support the development engineer with automatic maintainability evaluations reducing even further the maintenance specialists' support?

That was exactly the objective stated for this thesis research: To create a model to improve maintainability parameter analysis during the virtual development in PDP aiming to overcome the identified gap. The model (Figure 3.6 and Figure 3.5**Figure 3.7**) brought two different functions: i/ to seek parts in a CAD model structure highlighting golden components for aftermarket; and ii/ to evaluate automatically fasteners access with associated tools. Maintainability directives were also referred to, in order to provide extra guidelines on how to review a product from this parameter perspective.

The development of the plug-in with C language being based on a CAD software enabled tests in the exact environment engineers are normally using to develop their products on the day-to-day business. Also, it is important to highlight the contribution of the survey with real mechanics which supported the tool development by adding parameters to evaluate fasteners' access levels (specific objective).

Ergonomical aspects were also included in the research once a P95 hand, comparable with available literature, was added in the plug-in with different positions enhancing the tool capability to evaluate fastener's removal (specific objective).

The plug-in was verified and validated in four different steps. In the first part, validation models (Table 3.2) were utilized to evaluate the entire plug-in functionalities serving as removal barriers. Such validation models were deeply investigated in order to create the right scenario for fasteners' removal analysis answering one of the proposed specific objectives. Even though most of the tests performed in a proper way, proving that the plug-in was actually finding the right removal space, some improvements were already noticed and reworked such as the need for different hand positions and the necessary alignment between fastener and tool surface in order to not misjudge top barriers investigations. Delta, acceptable and maximum angles configurations were tested and approved. Such tests were important to improve the maturity level of the plug-in.

On a second assessment Popescu and Iacob (2013) proposed rig was tested. Beyond a regular verification, similar to those performed on the previous validation models, other plug-in features were assessed. Golden components function presented a good result as selected part could easily be identified. Plug-in configurations such as number of components and safety multiplier were concluded to be properly functioning.

When testing against Junior (2005), plug-in actually performed appropriate analysis (even reverting Junior's results) but with too long lead-times. Golden components search on a complex product (complete engine) also worked even though some poor processing time was also perceived. Although different tests were executed to reduce response time, by reworking the CAD module, the plug-in did not succeed to perform the analysis in a reasonable timeframe. Nevertheless, the thesis model showed several different improvements compared to Junior's plug-in:

a. Main components are tracked: golden component from a maintainability perspective are highlighted.

b. Flexibility: it needs only the screw length to start performing an access analysis and covers any removal angle available with no predefined angled swept volumes (as proposed by JUNIOR, 2015);

c. Independence: interference analysis is delivered demanding no extra evaluation from the final user;

d. Extra data: average angle and number of movements needed to perform the fastener complete removal is delivered;

e. User friendly: based on predefined acceptable angle (collected from mechanics' survey) thesis plug-in delivers a colour result showing to the designer how good the access solution is.

The time demanded by the thesis plug-in to perform the evaluation though was considered to be so high that its usage on real life maintainability analysis would not be feasible. The interference analysis volume was not effective enough even if number of components were reduced to 12 only (complete engine had hundreds of parts).

On the last and fourth verification, a group of ten development engineers answered a survey (Appendix E) after performing some tasks by using the plug-in. The CAD module (Figure 4.70 – Appendix G) used as a reference during the survey was selected after few issues were found with different complex CAD modules, lack of another hand ergonomic position and, again, long lead-time to perform maintainability analysis.

From the mixed experience level group survey the following conclusions can be extracted:

a. The time needed to perform the maintainability evaluation was slightly lower when using the plug-in compared to the analysis without the tool (group B);

b. With the plug-in all analysis were correct. This was not the case for the youngest designer which incorrectly performed wrong assumptions when not using the tool. Therefore, the plug-in levels the users leading to the right answer reducing the experience needed to perform maintainability analysis;

c. Designers complained that without the usage of the plug-in, assesment was feeling based. With the the tool aid, reliable results are expected with greater precision levels;

d. A greater level of details are given: number of movements, removal conclusion (green, red or yellow colour to indicate the analysis conclusion), among others;

e. Reduced work level as the plug-in performs the analysis by itself;

f. Processing time was perceived as an issue: even though it was recognized that the global interference function is already very time consuming on PTC Creo Parametric originally;

g. Qualitative ergonomic analysis;

h. Possibility to use the plug-in in the conceptual phase reducing reworks on design reviews.

The best outcome from the survey was that most engineers would use the plug-in their daily activities (nine out of ten) if the tool was to be available.

The engineers also gave a good feedback on the golden components function finding it easy to find the highlighted components. However, they also raised the necessity to create a strong connection with PDP in order to use it in the right moment and with the proper search criteria (as product is always evolving). This need in fact, is answered by the maintainability analysis flow proposed by Figure 3.5.

Answering questions raised on Chapter 1, based on the obtained results, can be inferred that the model assists the development engineers to improve the application of the maintainability parameter in a more flexible way being less dependent on service experts. The provided model, in a user friendly manner, supports experienced and junior engineers to anticipate maintainability analysis reducing possible reworks on design reviews. The processing time though is a drawback that needs to be solved when working with complex products modelled with CAD module files.

The thesis objective was completely fulfilled.

5.2 Contributions

The thesis research was able to contribute with a new maintainability model concept which supports designers to perform maintainability analysis even with low experience level.

The tool, embedded in a plug-in, offers the possibility to track the golden components prioritizing the analysis from the start.

By knowing in advance which components have to be examined from a maintenance perspective, development engineers are able to verify a product fasteners accessibility in a simple and automatic approach.

Comparing with Junior (2015) plug-in concept, the thesis model framework supplies a more flexible and independent solution, being possible to adjust to any CAD module scenario.

Another very important contribution is the interference volume proposal. Even though tests faced very time consuming evaluations to reach final results, the interference model concept will be a strong feature to improve processing time reduction in complex products (specific objective). Mostly based on engineers' feedback, it has been understood that the issues faced with the processing problems are directly related to the global interference function in PTC Creo Parametric, and not in the concept proposed by the research.

5.3 Applications of the research

The proposed maintainability model concept may be applied in any product development based on 3D CAD environment. The same plug-in structure may be developed in different software platforms if desired.

However, a broader level of fasteners, tools and hand positions must be available in order to be feasible to use the plug-in in the day-to-day working conditions.

5.4 Suggestions of future work

Some suggestions for future work proposals are given next:

a. Continue the investigation of processing time issues, either by studying deeper the PTC Creo Parametric solution, or moving to other software platforms;

b. Increase the maintainability model offer by improving the fastener analysis from one to multiple analysis sequentially;

c. Create an extra function to just present a complete tool board composed of different virtual tools (similar to any tool board from workshops or tools from mechanics trolley);

d. Increase the tools and hand positions database with current plug-in concept;

e. Improve the fastener analysis function by creating an evaluation report showing exactly where the clashes are happening;

f. Add a functionality to consider the angles from a fastener hex screw head (60°) when using a regular wrench, avoiding mis-judgements with smaller movement angles available. The same issue would not happen with star spanner and/or ratcheting wrench;

g. Improve maintainability model by creating a stronger link between space claims and golden components functionality.

SCIENTIFIC PRODUCTION IN THE PERIOD (2013-2017)

MOSCHETO, A. D.; CZIULIK, C.; JUNIOR, S. M.; SULEVIS, M., Space claim analysis for addressing maintenance of key components in complex products. **Assembly Automation**. Vol. 37, Issue 1, p. 71-83, 2017.

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APPENDIX A – SET OF DIRECTIVES FOR MAINTAINABILITY

From Moscheto (2009) a set of directives related to the maintainability parameter was established based on author’s know-how and checklists from Blanchard and Fabrycky (2006), Blanchard, Verma and Peterson (1995) and MIL-HDBK-470A (1997).

The directives do not considerer aspects that are exclusively related to on board electronic diagnosis or supportability as they are not part of the thesis’s scope. The suggested set of directives is given in Table AP.1:

Table AP.1 – Set of Directives for Maintainability

(cont.)

Item	Description	Analysis		
1	Maintainability requirements (applied in the Task Explanation & Conceptual phases)	Yes	No	Comments
1.1.	Were all maintainability's qualitative and quantitative requirements set?			
1.1.1.	Are the requirements realistic and can they be achieved/checked with the resources allocated for validation in maintainability?			
1.1.2.	Do they cover all negative aspects in the product's current version (in the light of maintainability)?			
1.1.3.	Were the product's innovative concepts modelled taking into consideration the maintainability aspects?			
2.	Accessibility			
2.1.	Is there access to "key" components without the eventual need of removing peripheral components?			
2.1.1.	Do components under preventive maintenance and/or daily maintenance allow free access for services or simple inspections?			
2.1.2.	Are there exit routes duly allocated (solidified), for key-components (in 3D modelling) to ensure the space necessary to carry out maintenance services?			
2.2.	Are there access lids, adequate in terms of size and form, which allow easy access to the component, in case of an eventual replacement?			
2.3.	The access to the following components is guaranteed:			
2.3.1.	All fixing elements;			
2.3.2.	Connectors, sensors and control units;			
2.3.3.	Testability and/or adjustment points (e.g. nipple to check engine's oil pressure).			
3.	Was product standardization incorporated to its maximum?			
3.1.	Are the proposed new parts' contents within the limits given by the project?			
3.2.	Was the variety of fixing elements reduced to a minimum?			
3.3.	Was the range of connectors standardized, without becoming a risk for the product (e.g. possible inversions in re-assembling)?			
4.	Fixing elements			
4.1.	As feasible, were the fixing elements chosen in order to be quickly removed?			
4.1.1.	Do the screws/nuts have the shortest length possible?			
4.1.2.	In case fixing nuts were used, were welded nuts used?			
4.2	Was the number of fixing elements reduced to a minimum?			
4.3.	Was the application of controlled torques, to fixing elements, reduced?			

Table AP.1 – Set of Directives for Maintainability

(cont.)

4.4.	For access lids:			
4.4.1.	Were spring-gas or lock systems used as fixing elements in the lids that are daily used?			
4.4.2.	Were ¼ turn (or equivalent) fixing elements used in the access lids that are weekly used?			
4.4.3.	Were screws/nuts used in other cases?			
4.5.	Are fast-coupling connections used in pneumatic and hydraulic systems?			
4.6.	Are clamps chosen in order to minimize the repair time?			
4.6.1.	Do clamps have a set-torque in order to avoid over-torque?			
5.	Simplification			
5.1.	Was the system's complexity kept at an acceptable level?			
5.2.	Are all parts absolutely necessary?			
5.3.	Were the connections between different modules facilitated, in order to avoid unnecessary adjustments, regulations or calibrations?			
6.	Tools			
6.1.	Were the fixing elements chosen in order to avoid the use of tools?			
6.1.1.	If negative, were they chosen having in mind universal tools instead of special tools?			
6.2.	Were existing universal/special tools, used in previous products, considered before the proposal of any new concept that would demand a new tool?			
7.	Modularity			
7.1.	Was the product modularized in order to allow fast change of components?			
7.2.	Is there any possibility of contamination between different modules?			
7.3.	Are there guides to facilitate the assembly between modules?			
7.4.	Was the number of different variants, in the same product, kept to a minimum?			
8.	Poka-yokes			
8.1.	Were poka-yokes used to avoid mistakes during assembling/disassembling?			
9.	Testability			
9.1	Were test points made available in order to facilitate product diagnosis?			
9.1.1.	Were the test points' functionally allocated and marked in order to facilitate maintenance?			
9.2	Were inspection areas made available in order to guarantee inspections and adjustments?			
9.3.	Were electric whips designed to facilitate diagnosis (e.g. pin-box and break-out cables assembling)?			
10.	Ergonomics			
10.1	Was components' mass minimized?			
10.1.1.	Are there lifting alternatives for heavy components (e.g. lift holes, etc.)?			
10.2.	Were accesses duly planned in order to ensure space for the mechanic and tool?			

Table AP.1 – Set of Directives for Maintainability

(conclusion)

10.3.	**Were inadequate repair positions avoided (feet not on the floor, lay-down positions, among others)?**			
10.4.	**Were repairs planned to be performed by a single person?**			
11.	**Service and lubrication / preventive maintenance**			
11.1.	**Was lubrication minimized?**			
11.2.	**Was the time for preventive maintenance minimized in order to ensure a greater availability?**			
12.	**Environment**			
12.1	**Was the maintenance environment, in the organizational and intermediate levels, considered in the development of a product's concept?**			
13.	**Adjustments, regulations and calibrations**			
13.1.	**Were adjustments, regulations and calibrations avoided to the maximum extent possible?**			
13.2.	**Was the intervention interval for adjustments, regulations and calibrations organized so that they only occur in pre-scheduled preventive maintenance?**			

APPENDIX B – TEST PARTS FOR ANGLE OF ACTUATION ANALYSIS

The parts below were designed and manufactured in order to support a practical analysis with mechanics. Different angles of actuation were simulated and mechanic's feedback were gathered in order to define what is a good or bad twisting movement angle when removing a fastener.

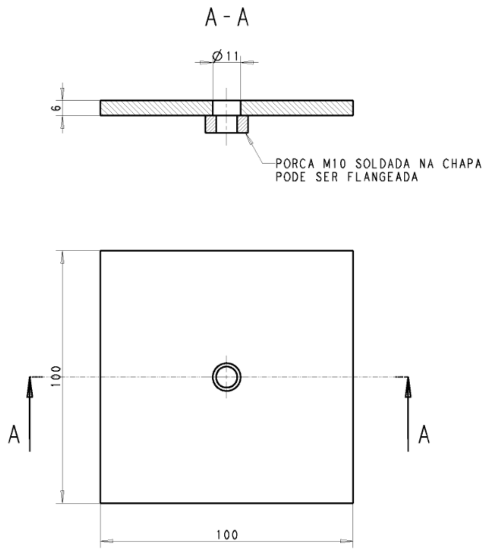

Figure AP.1 – Test Part 1 (mm)

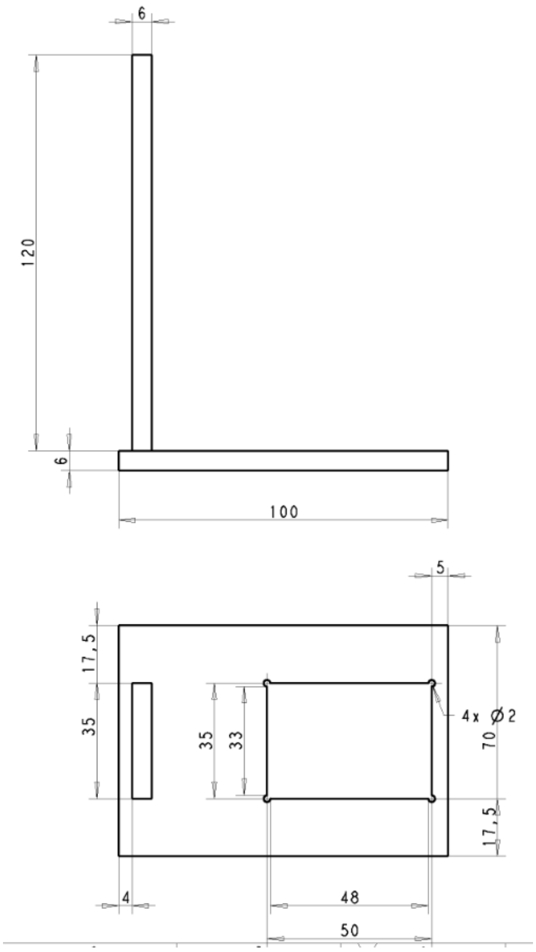

Figure AP.2 – Test Part 2 (mm)

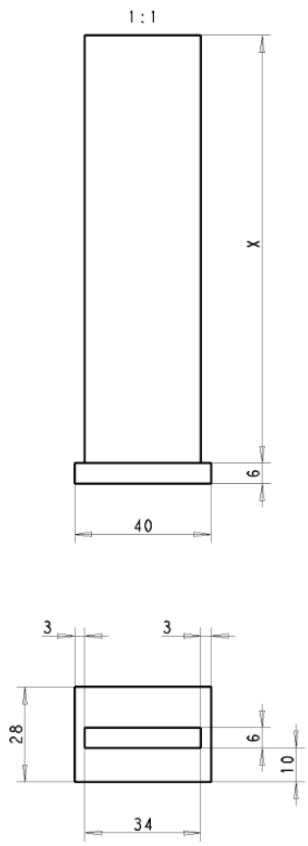

Figure AP.3 – Test Part 3 (mm)

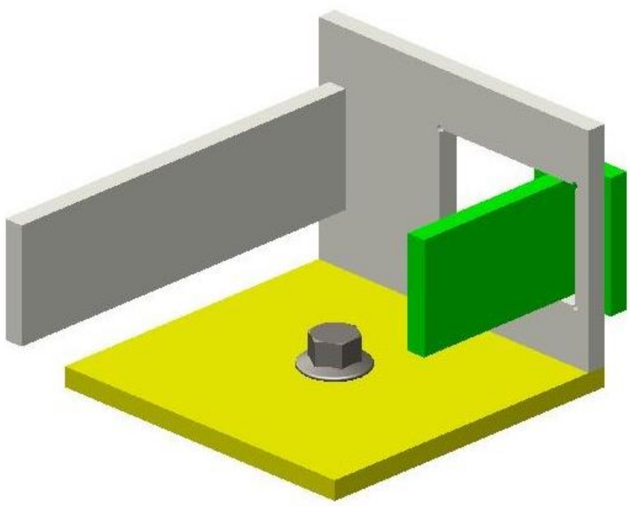

Figure AP.4 – Complete test component view

APPENDIX C – PRACTICAL TEST AND SURVEY WITH MECHANICS

The parts proposed on Appendix B were used in a practical test with 13 mechanics. Average of 16 years of working experience on a commercial vehicles industry workshop.

Different angles of actuation were proposed and mechanic’s feedback were gathered in order to define what is a good or bad twisting movement angle when removing a fastener.

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A – Mechanic identification

Name: ____

Age: _____________Years of experience as mechanic: _______________________

B – Fastener removal analysis

1. Practical test - preferred angle of actuation when removing a fastener?

- ☐ 15º
- ☐ 30º
- ☐ 45º
- ☐ 60º
- ☐ 90º
- ☐ Other: ____________

2. Practical test - maximum angle of actuation when removing a fastener?

- ☐ 15º
- ☐ 30º
- ☐ 45º
- ☐ 60º
- ☐ 90º
- ☐ Other: ____________

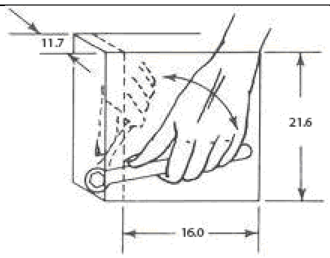
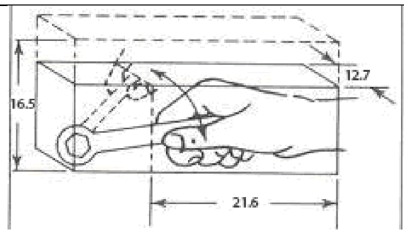
3. Which hand position do you prefer when removing a fastener?

- ☐ 1
- ☐ 2

Comments:

____

____

1	2
 	

4. When deciding to automate fasteners removal, which criteria do you normally consider? (e.g.: ratcheting wrench, power-pneumatic tools, among others)

☐ Space available

☐ Number of fasteners to be removed

☐ Time gains.

APPENDIX D – COMPUTER SPECIFICATIONS

Computer specification used throughout the verification and validation is presented on the following figure.

Figure AP.5 – Computer specification

The next computer specification was an example given from one of the participants from the verification and validation phase showing how powerful a dedicated CAD machine can be to support CAD analysis. Unfortunately it was not possible to test the plug-in on such computer as it held a different PTC software version.

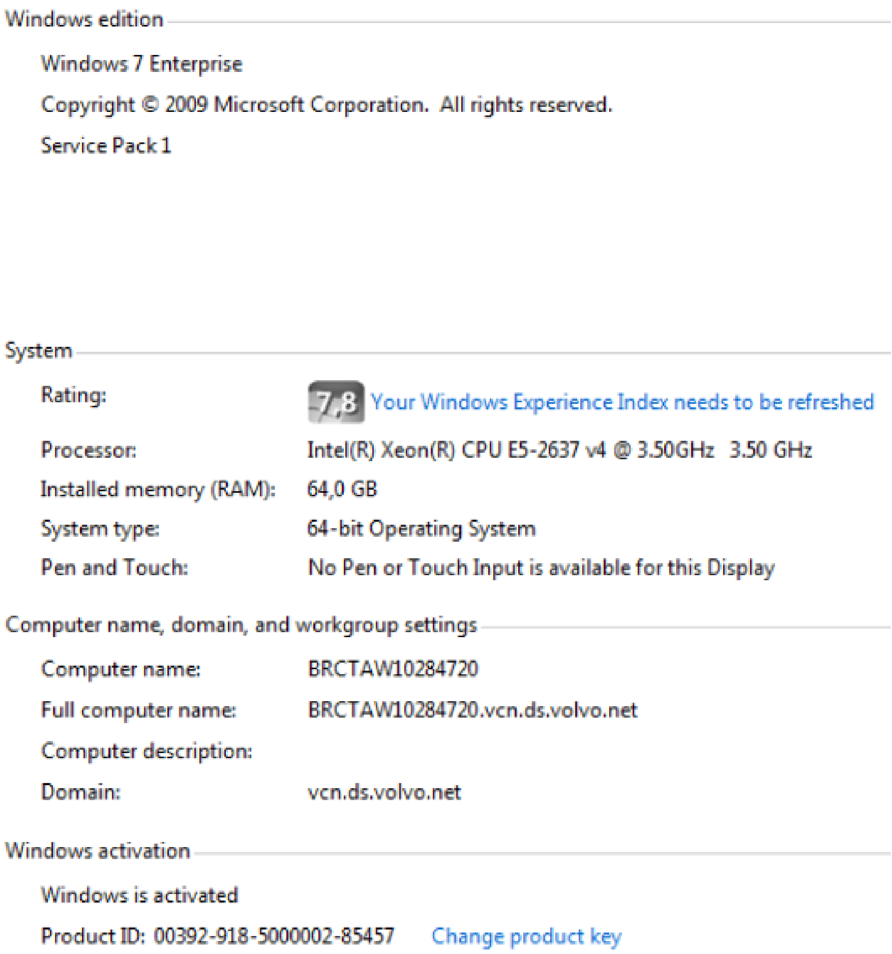


Figure AP.6 – Example of other computer specification used for CAD work

APPENDIX E – CASE STUDY FOR VERIFICATION AND VALIDATION

A case study (Figure 4.70) was applied with two groups of engineers. First group (A) had the aid of the plug-in developed by this research. The second group (B), as a start, just the case study model, a library of 3D universal tools (regular wrench) and a virtual P95 hand were supplied. After the test was finished for the second group, a new round started but now with the aid of the research plug-in.

The following questionnaires were used to support groups A and B:

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Questionnaire A

A – Participant identification

Name: ____

Age: _____________Years of experience as CAD specialist:___________________

1. From a maintenance background in automotive industry how do you consider yourself:

   ☐ A beginner

   ☐ I have a reasonable experience

   ☐ I am a maintenance expert

   ☐ I know nothing about vehicle maintenance

   ☐ Other: ____________

B – Case study presentation

The following CAD module is available in PTC Creo for your analysis. The three screws presented in the Figure AP.5 below has to be analysed whether there is enough maintenance space for their removal or not with a regular wrench with a manikin P95 virtual hand.

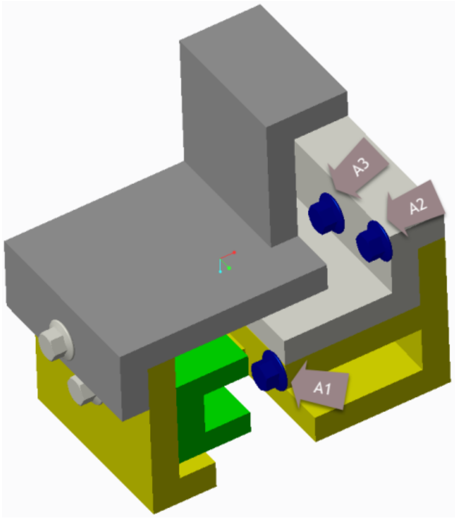

Figure AP.7 – Case study CAD module

In order to support your maintainability analysis you will apply a plug-in developed by this thesis research presented on Figure AP.6. Further explanation will be given by the thesis researcher along the test if needed.

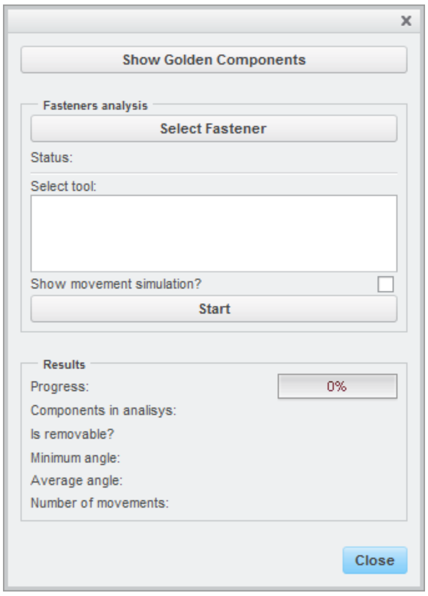

Figure AP.8 – Plug-in screen

C – Case study – test details and perceptions

2. Test duration time: ______________

3. Was it possible to remove the aimed fasteners - screws A1, A2 and A3?

A1	A2	A3
☐ Yes	☐ Yes	☐ Yes
☐ No	☐ No	☐ No

Comment:

____

____

____

4. Do you perceive a gain to apply such plug-in to perform maintainability analysis (valuable feature in a CAD system)?

☐ Yes.

☐ No.

Comment:

____

____

5. If this plug-in would be available in your daily use, would you make use of it?

☐ Yes.

☐ No.

Comment:

____

____

6. Which further improvements do you foresee for such plug-in?

Comment:

____

____

____

____

____

D – Golden component case study – test details and perceptions

You have been provided with a complete engine model. Now press the “Show Golden Components” button. Results expected are similar to Figures AP.7 and AP.8. The idea of this function is to support engineers to track key components for the aftermarket during 3D modelling, making it easier to define which components shall be prioritized in a maintainability analysis

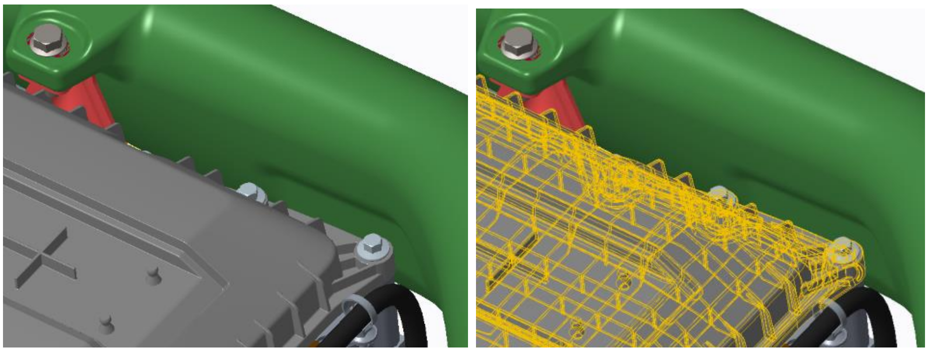

Figure AP.9 – Golden component usage – valve cover

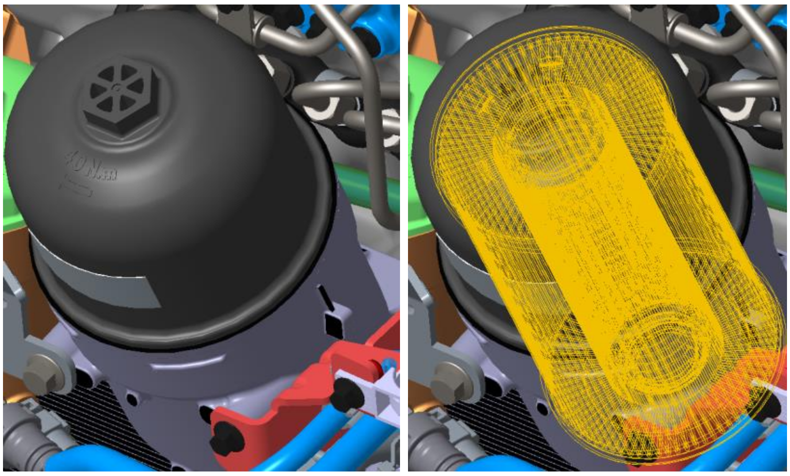

Figure AP.10 – Golden component usage - filter

7. Do you believe this function is a helpful tool to support engineers’ maintainability analysis?

☐ Yes.

☐ No.

Comment:

____

____

8. Was it easy to identify the golden components when using this function?

☐ Yes.

☐ No.

Comment:

____

____

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Questionnaire B

A – Participant identification

Name: ____

Age: _____________Years of experience as CAD specialist:___________________

1. From a maintenance background in automotive industry how do you consider yourself:

   ☐ A beginner

   ☐ I have a reasonable experience

   ☐ I am a maintenance expert

   ☐ I know nothing about vehicle maintenance

   ☐ Other: ____________

B – Case study presentation

The following CAD module is available in PTC Creo for your analysis. The three screws presented in the Figure AP.7 below has to be analysed whether there is enough maintenance space for their removal or not with a regular wrench with a manikin P95 virtual hand. A regular wrench and a P95 hand are available as a prt file within the CAD module assembly file.

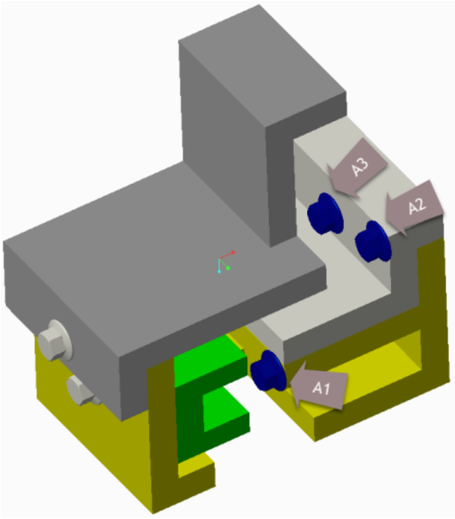


Figure AP.11 – Case study CAD module

C – Case study – test details and perceptions

2. Test duration time: ______________

3. Was it possible to remove the aimed fasteners - screws A1, A2 and A3?

A1	A2	A3
☐ Yes	☐ Yes	☐ Yes
☐ No	☐ No	☐ No

Comment:

____

____

____

4. Was it difficult to perform this maintainability analysis? Please comment your answer.

☐ Yes.

☐ No.

Comment:

____

____

D – Case study – test details and perceptions (now with plug-in usage)

In order to support your maintainability analysis you will apply a plug-in developed by a thesis research presented on Figure AP.8. Further explanation will be given by the thesis researcher along the test if needed.

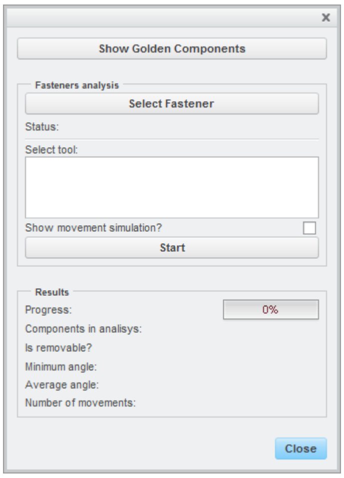


Figure AP.12 – Plug-in screen

5. Test duration time: ____________

6. Was it possible to remove the aimed fasteners - screws A1, A2 and A3?

A1	A2	A3
☐ Yes	☐ Yes	☐ Yes
☐ No	☐ No	☐ No

Comment:

____

____

____

7. Do you perceive a gain to apply such plug-in to perform maintainability analysis (valuable feature in a CAD system)?

☐ Yes.

☐ No.

Comment:

____

____

8. If this plug-in would be available in your daily use, would you make use of it?

☐ Yes.

☐ No.

Comment:

____

____

9. Which further improvements do you foresee for such plug-in?

Comment:

____

____

____

____

____

E – Golden component case study – test details and perceptions

You have been provided with a complete engine model. Now press the “Show Golden Components” button. Results expected are similar to Figures AP.7 and AP.8. The idea of this function is to support engineers to track key components for the aftermarket during 3D modelling, making it easier to define which components shall be prioritized in a maintainability analysis

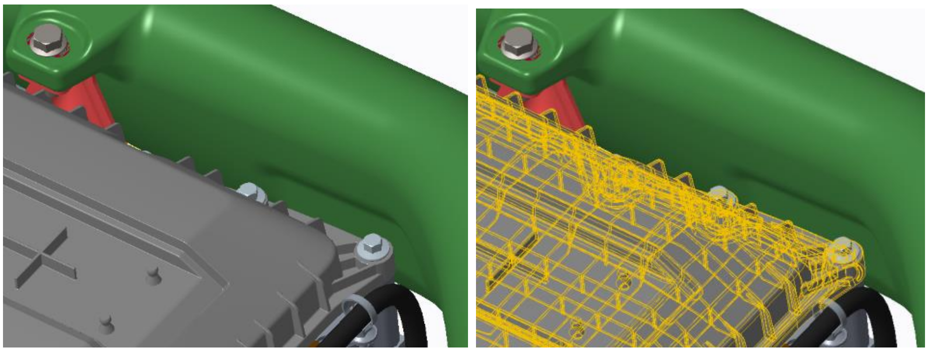


Figure AP.13 – Golden component usage – valve cover

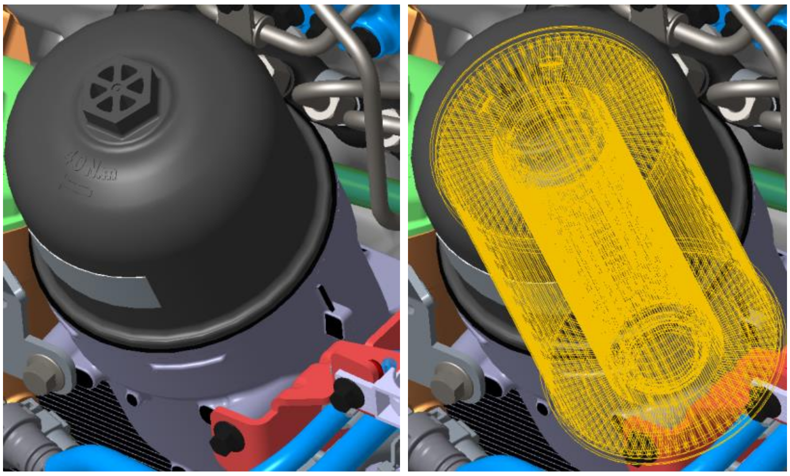


Figure AP.14 – Golden component usage - filter

10. Do you believe this function is a helpful tool to support engineers' maintainability analysis?

☐ Yes.

☐ No.

Comment:

____

____

11. Was it easy to identify the golden components when using this function?

☐ Yes.

☐ No.

Comment:

____

____

APPENDIX F – CASE STUDY ORIGINAL TEST MODEL

Original test model details presented in the following Figures.

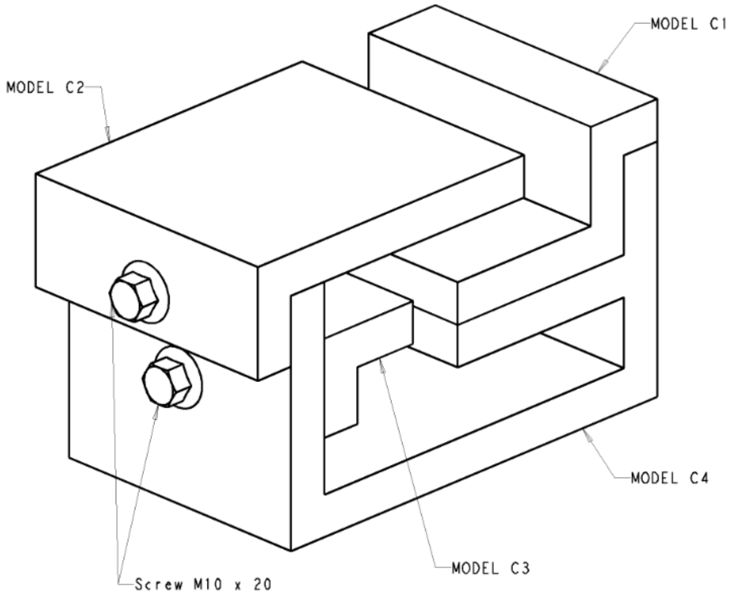


Figure AP.15 – Original test model

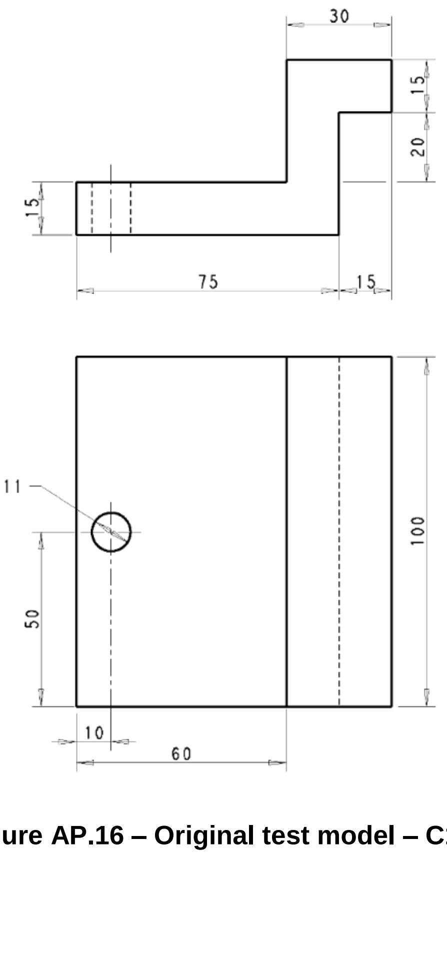


Figure AP.16 – Original test model – C1

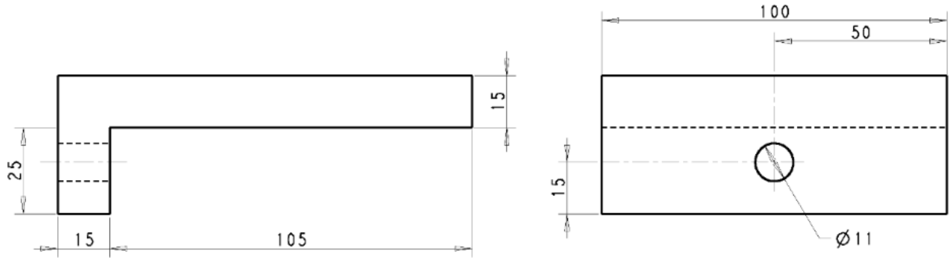


Figure AP.17 – Original test model – C2

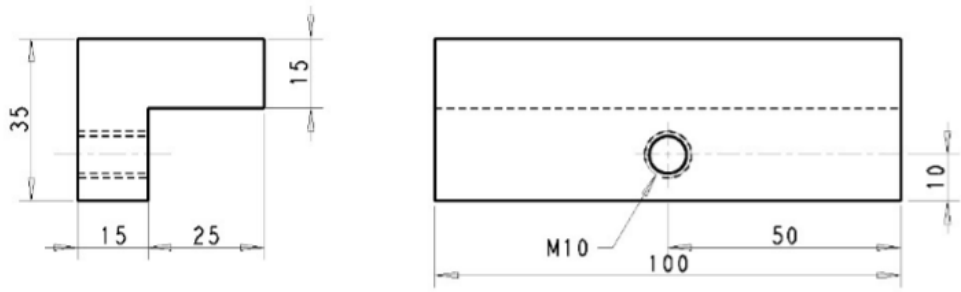


Figure AP.18 – Original test model – C3

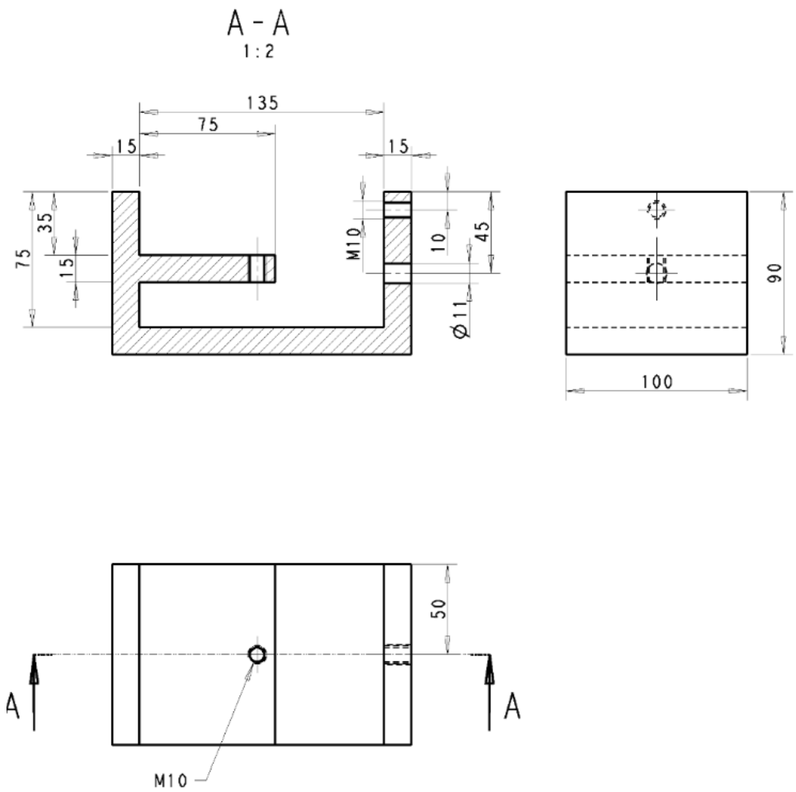


Figure AP.19 – Original test model – C4

APPENDIX G – CASE STUDY MODIFIED TEST MODEL

Modified test model details presented in the following Figures.

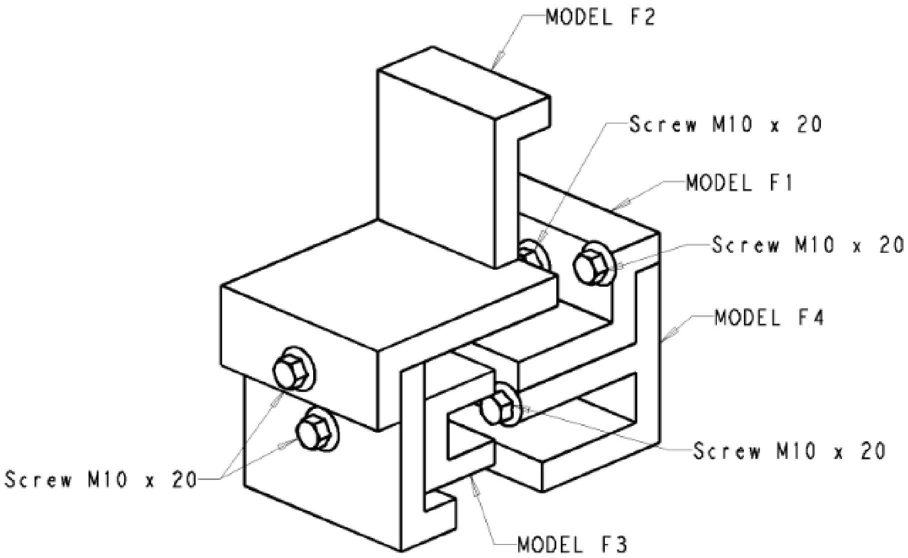


Figure AP.20 – Modified test model

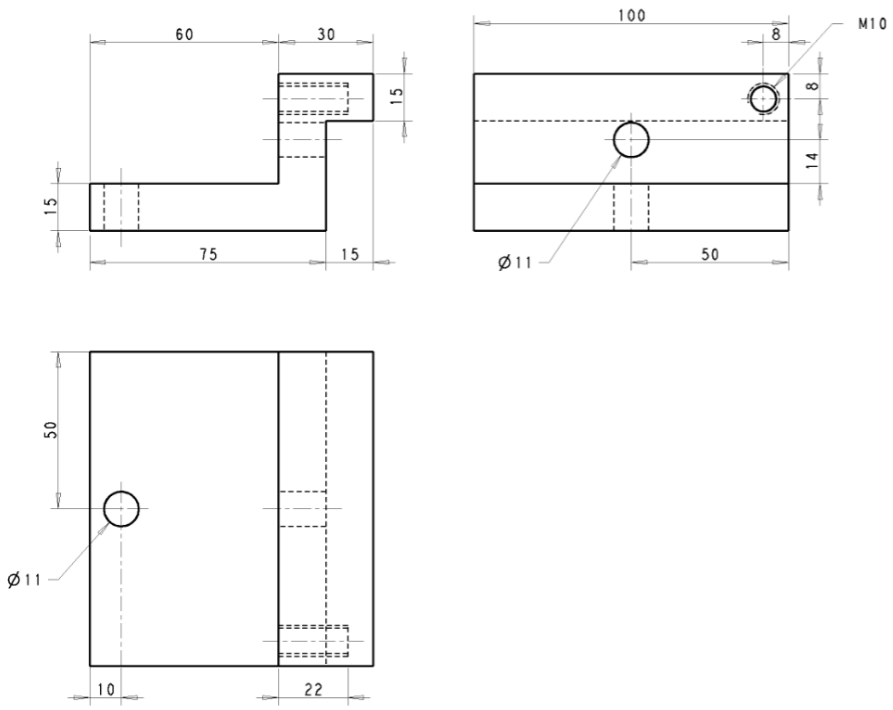


Figure AP.21 – Modified test model – F1

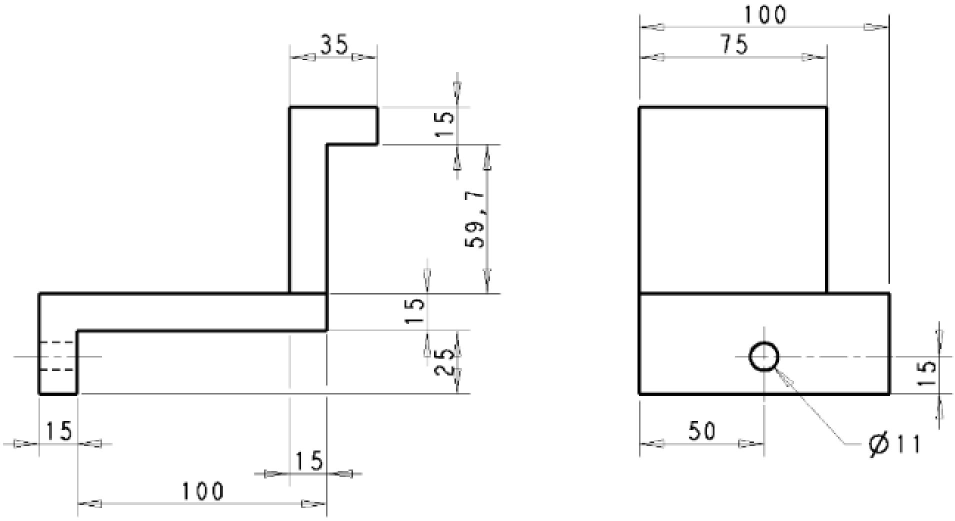


Figure AP.22 – Modified test model – F2

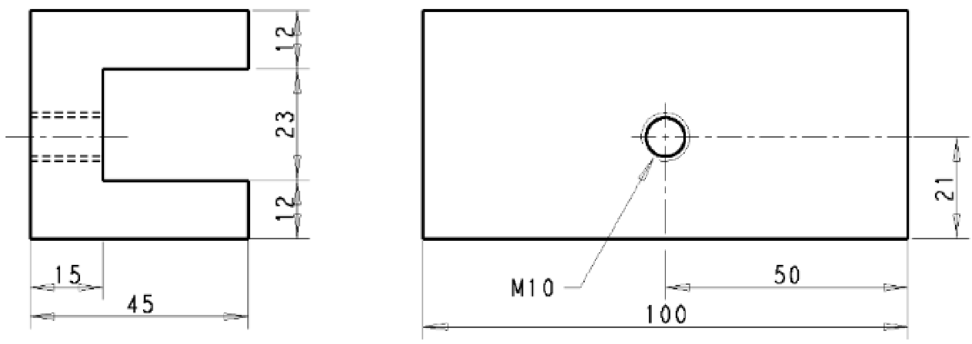


Figure AP.23 – Modified test model – F3

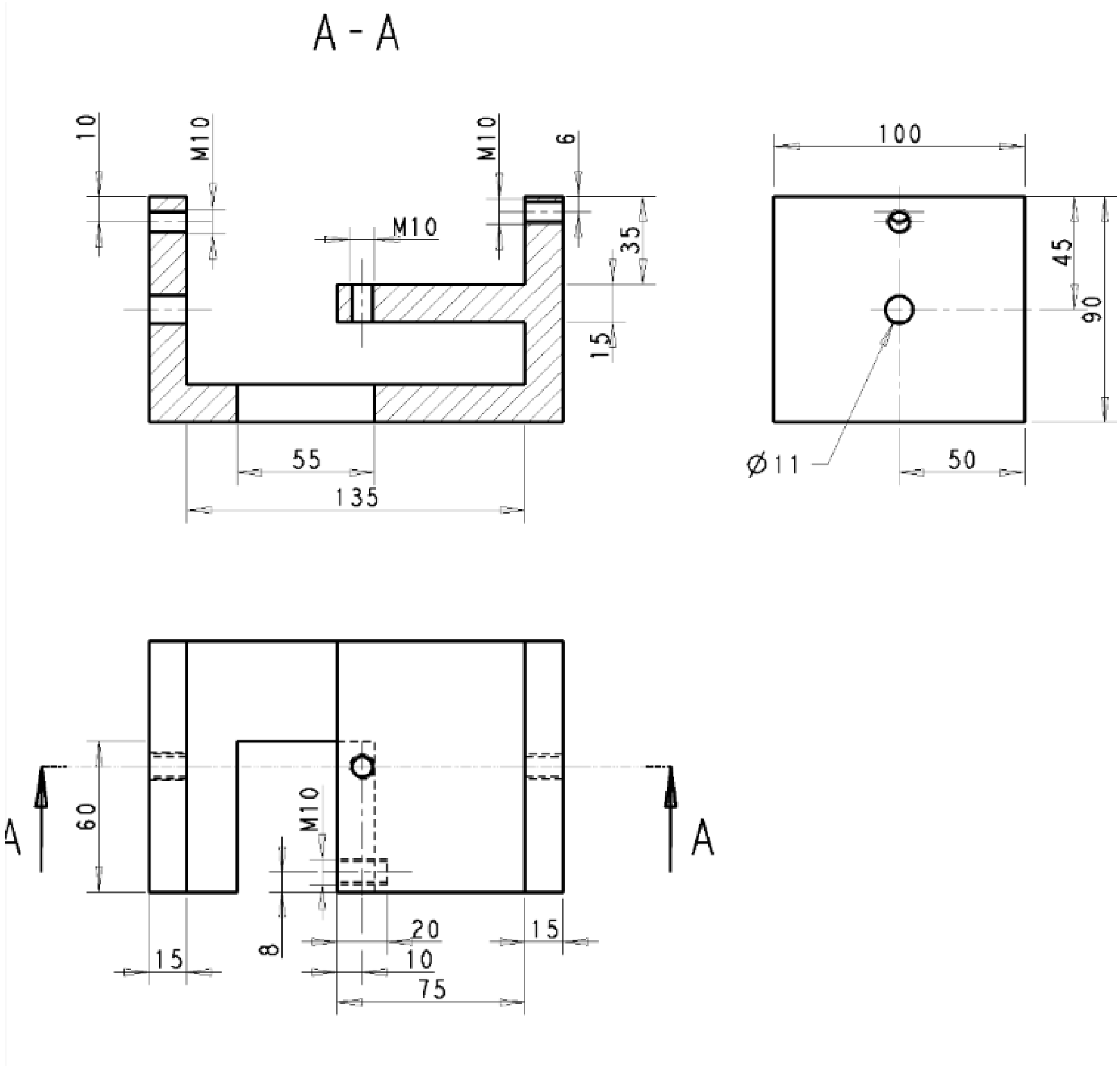


Figure AP.24 – Modified test model – F4

ANNEX A – ERGONOMICS – SPACES NECESSARY TO CARRY OUT MAINTENANCE SERVICES

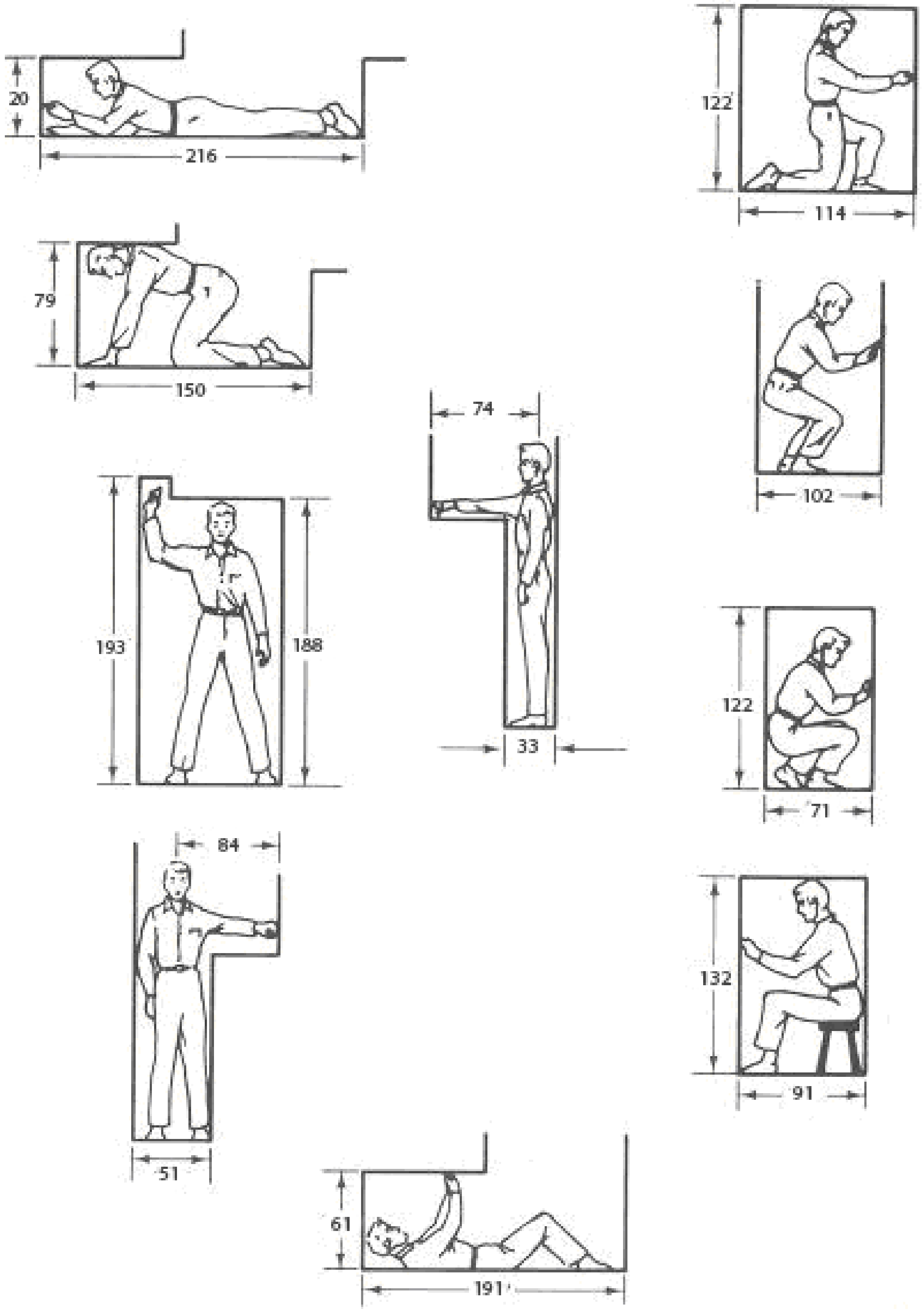


Figure AN.1 – Spaces required for different work positions (cm)
Source: Blanchard, Verma and Peterson (1995).

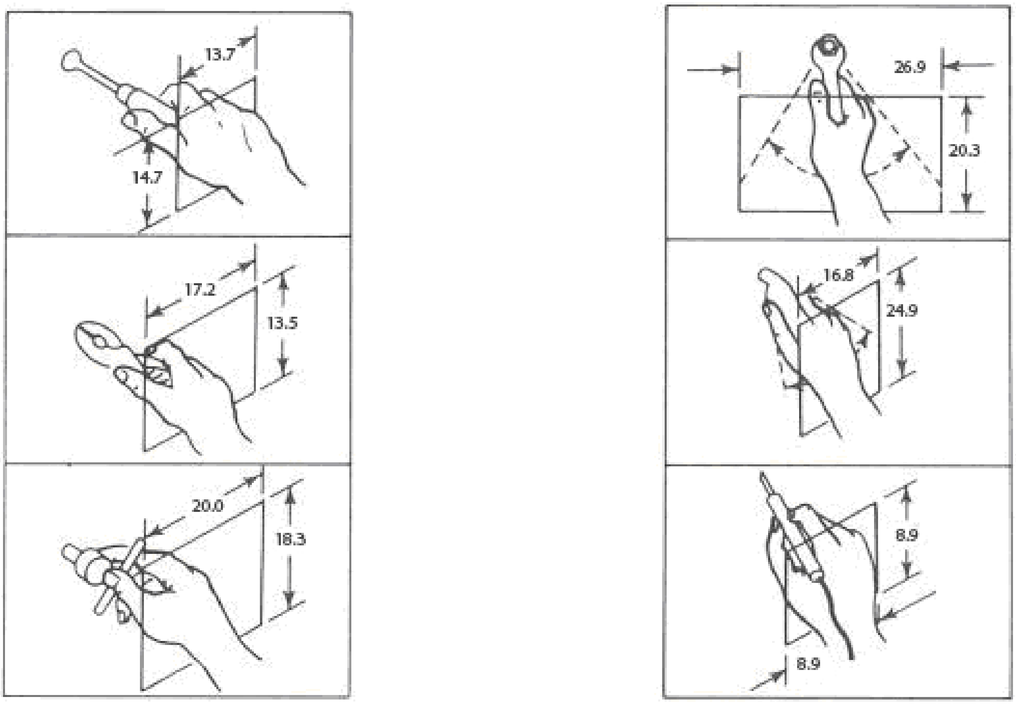


Figure AN.2– Space required to use universal tools in access windows (cm)
Source: Blanchard, Verma and Peterson (1995).

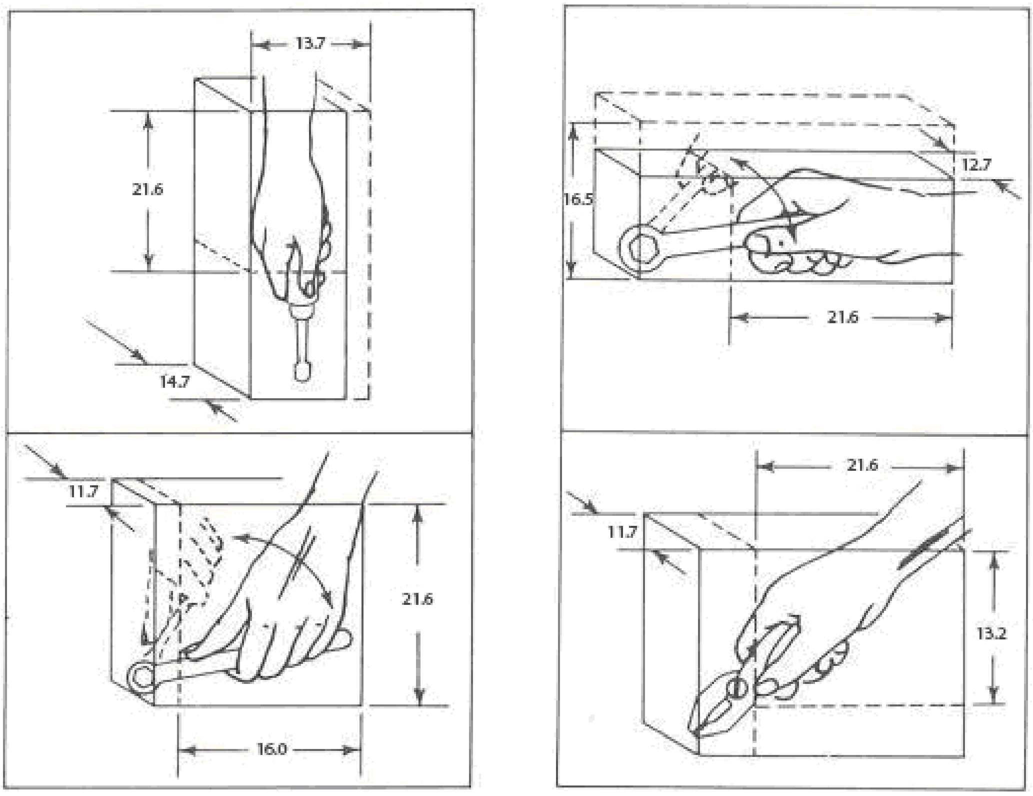


Figure AN.3– Space required to use universal tools (cm)
Source: Blanchard, Verma and Peterson (1995).

ANNEX B – FIXING ELEMENTS

Standard Screws

- This time is for all standard threaded fasteners such as; slotted head, Phillips head, and fillister head
- The time given is the time required to remove/replace the fastener from the hole and disengage/or engage it by several twisting motions of the hand (approximately 8 twists)
- Tool required is standard screwdriver (flat head, Phillips, or hex)

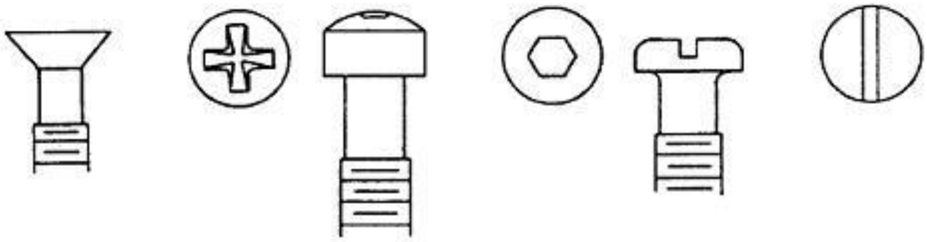


Figure AN.4– Examples of standard screws
Source: Adapted from MIL-HDBK-470A (1997).

Hex or Allen Set Screws

- This time is for hex or Allen type set screws
- The time given is for the time to tighten/or loosen a hexagonal type set screw using an Allen type wrench
- Tools required are hex wrenches or Allen type wrenches

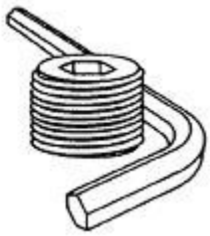
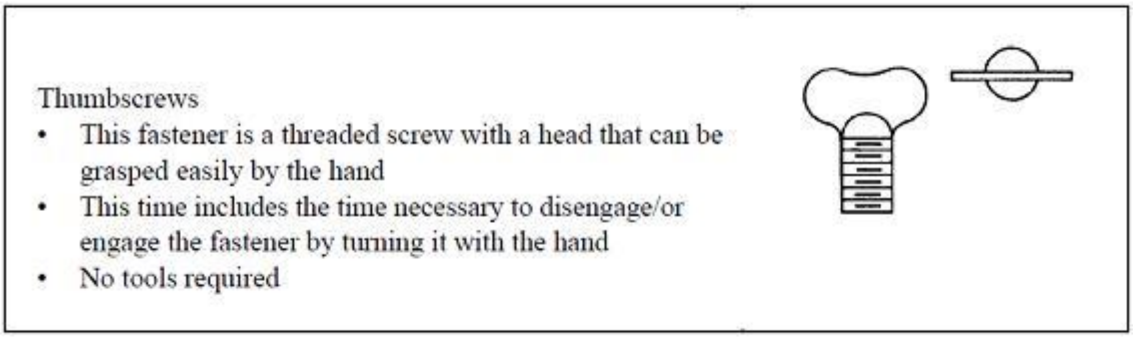


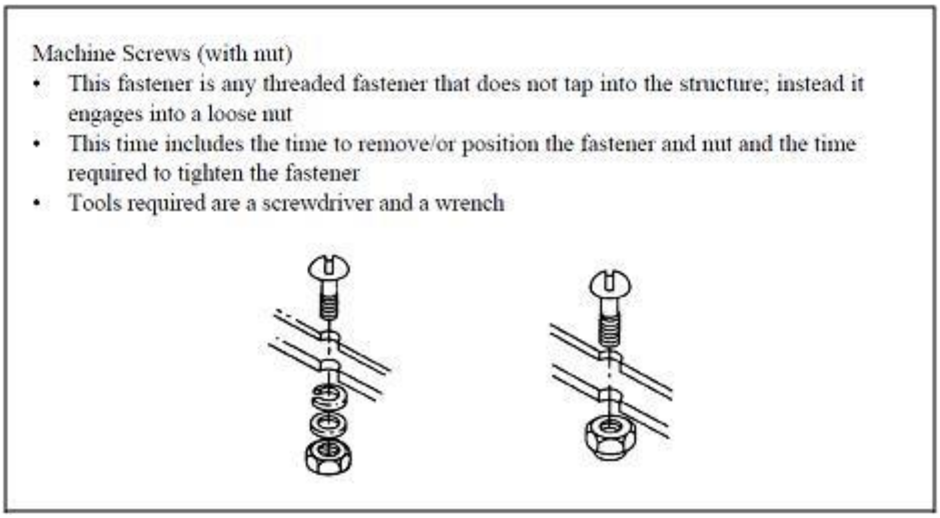
Figure AN.5– Example of hex or allen set screws
Source: Adapted from MIL-HDBK-470A (1997).



Thumbscrews

- This fastener is a threaded screw with a head that can be grasped easily by the hand
- This time includes the time necessary to disengage/or engage the fastener by turning it with the hand
- No tools required

Figure AN.6– Example of thumbscrews
Source: Adapted from MIL-HDBK-470A (1997).



Machine Screws (with nut)

- This fastener is any threaded fastener that does not tap into the structure; instead it engages into a loose nut
- This time includes the time to remove/or position the fastener and nut and the time required to tighten the fastener
- Tools required are a screwdriver and a wrench

Figure AN.7– Examples of machinery screw with counter-nut
Source: Adapted from MIL-HDBK-470A (1997).

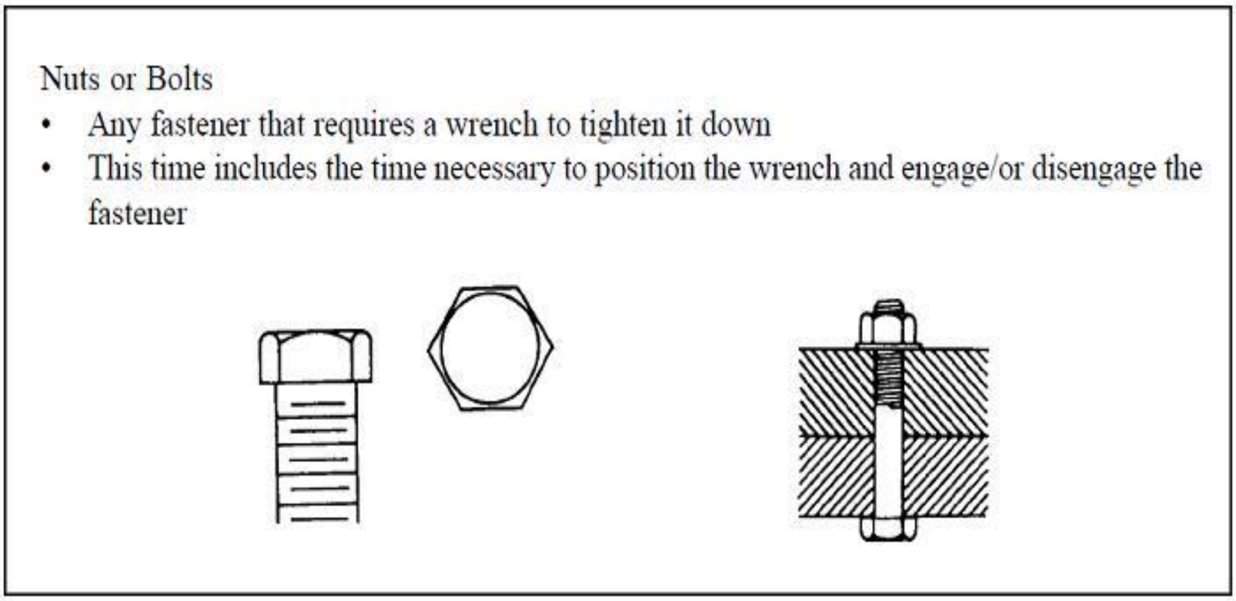


Figure AN.8– Example of nuts or bolts
Source: Adapted from MIL-HDBK-470A (1997).

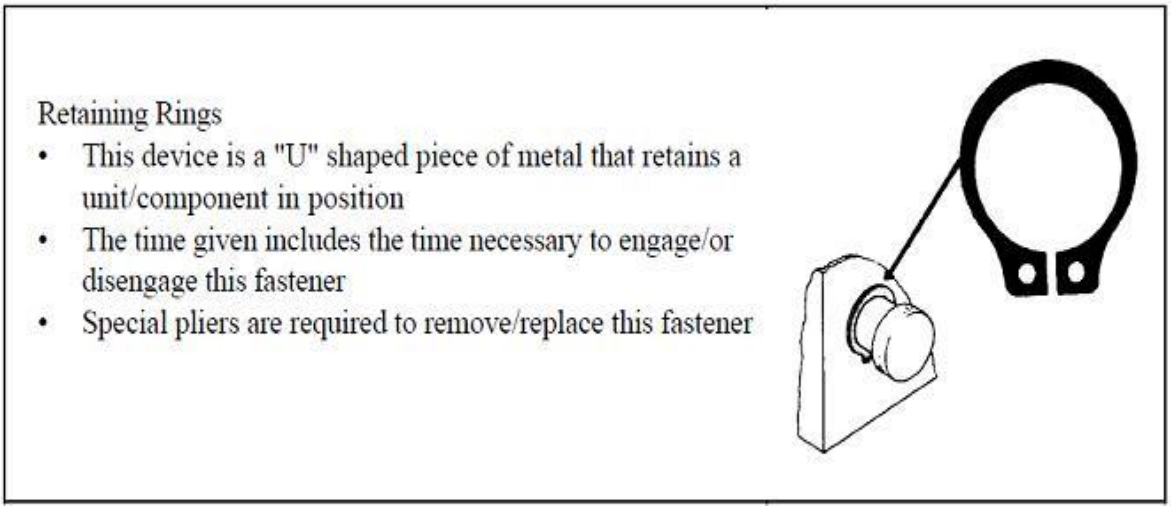


Figure AN.9 – Example of retaining ring
Source: Adapted from MIL-HDBK-470A (1997).

Drawhook Latch

- Any latch that is similar to the one shown here
- The time includes the time to engage/disengage the latch completely
- No tools required

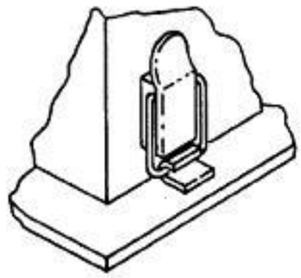


Figure AN.10 – Example of drawhook latch
Source: Adapted from MIL-HDBK-470A (1997).

Spring Clip Catch

- Any latch similar to the one shown here
- Time includes the time necessary to engage/or disengage the latch completely
- No tools required

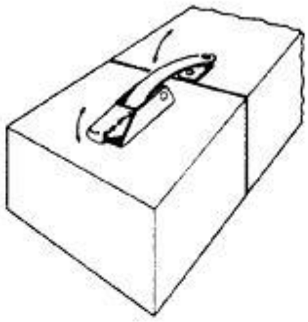


Figure AN.11 – Example of spring clip catch
Source: Adapted from MIL-HDBK-470A (1997).

Butterfly Latch

- Any latch similar to the one shown here
- Time includes the time necessary to engage/or disengage the latch completely. Normally consists of the time to lift the tab and turn it 90°
- No tools required

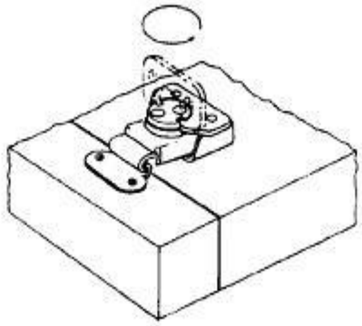


Figure AN.12 – Example of butterfly latch
Source: Adapted from MIL-HDBK-470A (1997).

Lift and Turn Latch

- Any latch similar to the one shown here
- Time includes the time necessary to lift the handle and turn it to unsecure or secure a door or panel
- No tools required

Figure AN.13 – Example of lift & turn latch
Source: Adapted from MIL-HDBK-470A (1997).