MAINTAINABILITY ASSESSMENT AT EARLY DESIGN STAGE USING ADVANCED CAD SYSTEMS

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Abstract: In mass production industries, the manufacturing equipments’ downtimes should be strictly avoided; and if failures occur the reparation time should be as short as possible to prevent from production losses that may affect dramatically the delivery delay. So, a high level of reliability and an easy maintainability are required for the machines tools used for high speed production. Many research works have been carried out about reliability estimation using simulation tools but there is a lack of efficient solutions for maintainability assessment and improvement at design stage. This paper proposes a framework for maintainability analysis within advanced CAD systems. The approach proceeds by four steps: the product decomposition, the digital mock-up semantic enrichment, the extended Design Structure Matrix building and the maintainability indicator calculation. In this procedure we consider the product nomenclature including not only its main components but also assembly artefacts. An application is presented to illustrate the approach.

Key words: 3D modelling, Maintainability, Extended-DSM, Reliability, Criticality.

1- Introduction

Many research investigations have been carried out about reliability estimation at design stage by suing simulation tools. Reliability engineering is the function of analyzing the expected or actual reliability of a product, process or service, and identifying the actions to reduce failures or mitigate their effects. Engineers analyzing reliability typically carry out reliability predictions, FMEA or FMECA, design testing programs, monitor and analyze field failures, and suggest design or manufacturing changes. The overall goal of reliability engineering is to make products and systems more reliable in order to reduce repairs, lower costs, and to maintain the company's reputation. To meet this goal best, reliability engineering should be done at all levels of design and production, with all stakeholders involved. Nowadays, current CAD and CAE systems provide good functionalities for products geometric modeling, structural and dynamic analysis. Most of these systems are aimed to functional and structural performances validation by numerical simulation. However there is a lack of efficient tools for the evaluation of new products behavioral performances like reliability, maintainability, safety or recyclability. The main reason of this deficiency is that such characteristics are semantically specified; and therefore additional information (data, knowledge and rules) are required to assess them.

In this paper we propose an approach for prediction of a complex product Maintainability using semantic data related to components’ Reliability and Criticality, and to assembly connections types between components. After the introduction on the motivation of this study, we present in section two, a brief literature review of recent research investigations related to maintainability evaluation at early design stage. In section three, the framework of our approach is outlined. Section four describes how this approach may be implemented into advanced CAD systems. To illustrate the approach, we outline in section five a case study on a subsystem of a NC milling machine tool. The main results and some future developments are discussed in the conclusion.

2- Related works

Reliability and maintainability estimation is a crucial problem when designing complex products that consist of different subsystems as in various industrial sectors like automotive, aeronautics, nuclear power plants, NC machine tools, and even commonly used products like washing machines, copiers, CAD plotters, etc. [CM1]. These last years some investigations have been done in developing solutions for reliability and maintainability prediction at the early design process, [CM1, DG1]. For this purpose, software packages like Relex Software [BR1] or ITEM Software [YG1] have been developed and are widely used in various companies, more especially by aeronautic and automotive constructors. But these tools are not coupled
to a CAD system to allow reliability assessment using the product model. For innovative products consisting of new design architectures and components, new assessment tools are required.

To face this demand, many tools using virtual reality technologies are proposed to verify new product functionalities, to test its ergonomics and to analyze its maintainability [VK1]. However, virtual reality platforms are often very expensive and complex to use during design process. So such systems are used by a few big manufacturers in the design of automotives, aircrafts or nuclear plants.

In the next section we propose a framework for maintainability assessment is described in details.

3- Product semantic modelling

The maintainability assessment procedure presented in Figure 1 consists of two main steps:
- the product semantic modelling and
- the maintainability indicator calculation.

In this section semantic modelling step is presented in more details. This step consists of three activities:
- the product decomposition,
- the semantic enrichment,
- the semantic matrix construction and the

These activities are described in the below.

3.1 – Product structural decomposition

The product is decomposed into its subsystems which may be decomposed again into detailed components. These components are assembled using assembly artefacts like fasteners or welding.

Based on the Gero’s classical FBS view points, the decomposition may be performed according to structural and/or functional criteria as shown in figure 2.

3.2 – Semantic enrichment

The semantic enrichment consists of adding information about components characteristics (material properties, surface quality ...), relative movements between components and about link types used to assemble components. ...

3.2.1 – Components semantic data

Traditional CAD model is mainly centered on geometric and topologic data and are semantically poor to support further analysis on the product maintainability. So, additional data required at component level as well as at assembly level.

At component level, we capture semantic data like:
- Material properties,
- Reliability,
- Criticality,
- Accessibility,
- Manoeuvrability.

3.2.2 - Assembly semantic data

At assembly level, we take into account:
- Connections between components and
- Interactions (friction) between them.

3.2.2.1 – Connections modeling

The classical assembly graph is shown in figure 3, generally indicates the binary information about the existence of connection between two components. Such graph does not capture about the type of connection between the components. In the next section, we propose to model the connection by providing...
The connection between components can be characterized by:
- one type of link as in figure 4 (single instance connection), or
- multiple kinds of link as in figure 5 (multi-instances connection).

By using components semantic data and this generic connection model instantiating for the assemblies, we can provide a semantic richer model. In the next section, we propose a representation of such a product model using the DSM structure.

3.3 – Semantic DSM
The semantic matrix is based on the traditional DSM Design Structure Matrix extended by including additional data describing the components characteristics and assembly link types.

<table>
<thead>
<tr>
<th>Components</th>
<th>C_1</th>
<th>C_2</th>
<th>-</th>
<th>-</th>
<th>C_3</th>
<th>-</th>
<th>-</th>
<th>C_4</th>
<th>Reliability</th>
<th>Criticality</th>
</tr>
</thead>
<tbody>
<tr>
<td>LinkType</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>LinkType</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>R_1</td>
<td>K_1</td>
</tr>
<tr>
<td>LinkType (C, C_i)</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>LinkType (C, C_j)</td>
<td>-</td>
<td>2</td>
<td>0</td>
<td>R_2</td>
<td>K_2</td>
</tr>
<tr>
<td>THRESHOLDS</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
<td>5</td>
<td>0</td>
<td>R_3</td>
<td>K_3</td>
</tr>
</tbody>
</table>

Table 1: Semantic Design Structure Matrix.

In this matrix, the components semantic data are stored into diagonal elements while assembly connections data are represented in non-diagonal elements. The semantic matrix is used as an input to the maintainability indicator calculation step.

4- Product Maintainability assessment
The maintainability is the ability of a product to be easily repaired when failures occur during the utilization. Different parameters may be considered to evaluate this characteristic: accessibility, links types, manoeuvrability, etc. Here, we consider the MTTR (Mean Time To Repair) as the maintainability indicator.
Based on this indicator, the designer can evaluate design solution and decide which are acceptable considering the minimum tolerable downtime duration specified by the end-user.

\[ I_m = T_{diagnosis} + T_{repair} + T_{test} \] (1)
Where:

- $T_{\text{diagnosis}}$ is the diagnostic duration required to localise the default components.
- $T_{\text{repair}}$ is the duration of technical maintenance tasks for repairing or changing the default components.
- $T_{\text{test}}$ is the duration of tests required to verify if the product works properly after repair. At the early design stage diagnosis and tests durations are difficult to be estimated. These times may be more or less long.

Then we will focus on the $T_{\text{repair}}$ term and we assume that this duration is the maintainability indicator commonly called MTTR (Mean Time To Repair). This characteristic is commonly considered as the most significant characteristic in maintainability analysis.

**MTTR assessment**

For a product consisting of $n$ components, if we assume that this product containing $k$ critical components as defined in (CM1) the MTTR can be estimated using the following expression (2).

$$I_{\text{maintainability}} = MTTR = \sum_{i=1}^{k} MTTR_i(C_i)[1 - R(C_i)] \quad (2)$$

Where:

- $MTTR_i$ is the duration required to remove critical component $C_i$ from the product assembly.
- $R(C_i)$ is the reliability of critical component $C_i$.

$$MTTR_i = \text{Min}\{\text{disassembly paths for critical component } C_i\} \quad (3)$$

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### 5- Implementation into advanced CAD system

Figure 6, shows the user interface of an advanced CAD system consisting of traditional CAD software with an add-on modules that implement maintainability assessment functionalities.

The proposed advanced CAD system is composed by a 3D CAD system and three main modules:
- the design review module,
- the Semantics data capturing module and
- the analysis module.

The design review module is used to perform the decomposition and provide the product part list. The semantic data capturing module consists of a components editor and assembly editor used to specify connections and components interactions. The analysis module allows to specify reliability and criticality and then to calculate maintainability indicator.

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### 6- Application to CN milling machine-tool

The approach is experienced using a subsystem of a CN milling machine tool, shown in Figures 7 to 9. Following the procedure presented previously, this subsystem has been decomposed into its components. Then the components and
their connections have been enriched semantically to build the semantic DSM. Then the maintainability can be estimated.

Figure 7: NC milling machine Subsystem

Figure 8: NC milling machine Subsystem

Figure 9: Multi-instances connection

7- Conclusions and future works
This paper presents a framework for maintainability assessment using a semantic model of the product digital mock-up. The generic product model proposed allows to capture components semantic data and assembly connections between components. This information is then used to estimate maintainability indicator for products under development at design stage. An application briefly presented has been outlined to illustrate the approach.

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