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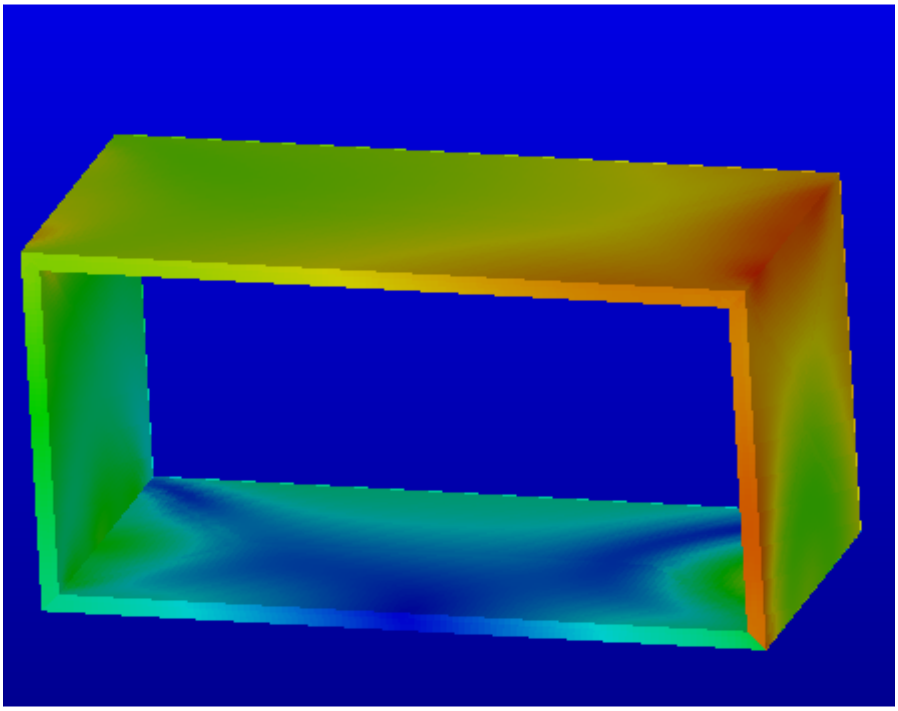

Non-rigid FE-based variation simulation for furniture

At IKEA via Wingquist Laboratory

Master's Thesis in Product Development

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Department of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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COVER:

A variation analysis result of the frame of the IKEA furniture VALJE.

Chalmers Reproservice

Gothenburg, Sweden 2016

ABSTRACT

This master thesis has been carried out between January to June of 2016 by Chalmers University of Technology students Dawei Tang and Kristoffer Zakrisson, as a collaboration between IKEA of Sweden AB (IoS) and Wingquist Laboratory of Chalmers.

Today, at the time of this thesis, IoS is using SolidWorks and its applications to model and analyze their products for tolerance. The SolidWorks integrated toolbox DimXpert is used to dimension and tolerance the individual parts of a product. This is followed by using the SolidWorks analysis application TolAnalyst to determine the assembly sequence of the product as well as determining the measures of interest for performing variation and contribution analysis.

IoS wants to further expand their franchise in the future. They want to involve more engineering skills in the process and also investigate alternative ways of working. This thesis is intended to be a part of this vision. In this thesis the current way of working using SolidWorks has been analysed against using the Computer-Aided Tolerancing (CAT)-tool Robust Design & Tolerancing (RD&T).

A dresser from the IKEA product range, Valje, was chosen for analysis. Using a product familiar to IKEA helped to demonstate to IKEA what benefits could come from implementing the RD&T software into their way of working. The product has been analyzed using as equal setups as possible in the two softwares. The simulation results gathered have been evaluated and the differences between the softwares and simulation methods have been pointed out. It has been found that RD&T gives more defined and accurate results since it analyses in 3D while SolidWorks analyzes in 1D at a time. This gives that RD&T considers rotations. RD&T non-rigid simulation can give more accurate results since the model takes material properties into consideration and allows the model to be overconstrained. This makes it easier to support the parts of the model and distribute the total variation more even over the areas of the product.

Keywords: variation, tolerance, non-rigid, dimension, RD&T, SolidWorks

ACKNOWLEDGEMENTS

During the work with this master thesis, we have been guided and assisted by a number of people. We would like to thank you all and express our gratitude for your involvement through the thesis.

Thank you Kristina Wärmefjord, Rikard Söderberg and Lars Lindkvist of Chalmers and Wingquist Laboratory for your support and guidance. Your expertise in RD&T has been of great value for us and for the result of this thesis.

Thank you Matti Pettersson, Tony Cederqvist and Håkan Käll of IKEA for your valuable information on the way of working with assemblies and tolerancing at IoS.
Thank you Björn Stoltz of IKEA for assisting us on how to work with material structures and other FEA related areas and for supplying us with material data.
Thank you Stefan Berglund for supplying us with a computer for SolidWorks analysis and for your guidance at our visits to Älmhult.

Last but not least we would like to thank our family and friends for their support during this thesis as well as throughout our whole time at Chalmers.

Gothenburg, May 2016

Dawei Tang
Kristoffer Zakrisson

ABBREVATIONS AND TERMINOLOGY

ABAQUS	A software package used for tolerancing pre/post CAE Process. Used in this thesis to create surface mesh sets.
CAT	Computer-Aided Tolerancing
CAE	Computer-Aided Engineering
DOF	Degrees of freedom
FEMAP with Nastran	A software package used pre/post CAE process. Used in this thesis for extracting midsurfaces of parts.
FEA	Finite Element Analysis
GD&T	Geometric Dimensioning & Tolerancing. A symbolic language used to specify form, size, shape, orientation and location of features on parts.
INP	ABAQUS file format. Used for describing mesh, accepted by RD&T for non-rigid simulation.
IoS	IKEA of Sweden AB. IKEA Head quarters located in Älmhult, Sweden
JT	Lightweight format. Used in e.g. Product Lifecycle Management (PLM) softwares and is accepted by RD&T for rigid simulation.
LMC	Least Material Condition
MMC	Maximum Material Condition
PCIs	Process Capability Indices
Ppm	Parts per million
RD&T	Robust Design & Tolerancing. A CAT-software used for tolerancing and analysis of e.g. variation
RSS	Root Sum Squared

RX, RY, RZ	Rotation around the X, Y and Z axes
TX, TY, TZ	Translation along the X, Y and Z axes
VRML	Virtual Reality Modeling Language. Triangulated file format used by RD&T for rigid simulation.

TABLE OF CONTENTS

1 INTRODUCTION

There is variation in all products and production processes. Variation might cause the produced products to visually look different from each other, not function equally or in worst case not function as intended at all. Because of products, production methods and processes are getting more and more complex in industries today, more work and effort is demanded on variation analysis, including dimensioning, tolerancing and other factors that contribute to variation, in order to achieve the results demanded.

1.1 BACKGROUND

IKEA Group is a world-leading home furnishing company, dedicated to create a better everyday life for people. In 2014, the turnover was 28,7 Billion Euro. The IKEA Group has 147.000 co-workers, 315 stores in 27 countries, with manufacturing done worldwide (59% in Europe). IKEA of Sweden AB (IoS), located in Älmhult, Sweden, is responsible for developing and supplying the global IKEA range to all IKEA franchisees.

Wingquist Laboratory is an internationally competitive competence center for multidisciplinary research within the field of efficient product realization. Wingquist Laboratory applies deep knowledge within its defined research areas on new research challenges, emerged from effective and efficient development of product families with high level of commonality, with respect to components, knowledge and manufacturing.

This master thesis is done in cooperation with Chalmers research group “Geometry Assurance and Robust Design” in Wingquist Laboratory.The reason for the thesis is of importance for IoS as well as IKEA´s customers. It should be assured that the assemblies of the IKEA produced products are customer-friendly. The base for accomplishing this is to set the right tolerances, while keeping the production costs low.
IoS vision is to raise the engineering skills in the way of working, a part of this vision is to implement advanced methods and tools. This thesis is a part of that process, evaluating new tools for creating a better everyday life for many.

1.2 PURPOSE AND GOALS

The goal of this thesis is to benchmark the current way of working at IoS against using the Computer-Aided Tolerancing-tool (CAT-tool) Robust Design and Tolerancing (RD&T) and present the results and a suggestion on software implementation at IoS. This shall be done by setting up and analyzing IKEA furniture using the two softwares. The results include suggestions on benefits of implementing RD&T at IoS as well as recomendations on how to structure and proceed with future work.

1.3 STAKEHOLDERS

The results of this thesis will primarily have effect on the way of working at the product and production department of IoS. The personnel at this department will be shown an alternative way of working which, if implemented, subsequently will affect the company as a whole in various ways.

Chalmers University of Technology and especially their representatives in Wingquist Laboratory are important stakeholders because of their variation simulation research and their collaboration with IoS.

1.4 CURRENT WAY OF WORKING

Today IoS are using the software SolidWorks to model their products. The products are dimensioned using the SolidWorks integrated toolset DimXpert and then tolerances are applied and analyzed using the SolidWorks application TolAnalyst. Parallel to this, finite element analysis (FEA) is done on the products using separate FEA software. The tolerancing of the products are defined according to Swedish ISO standard. IoS has not specified any geometircal requirements for the overall shape of an assembled product. Today the tolerancing is done without any limits but simply to achieve as low variation as possible. As a part of looking into other ways of working, requirements like these can be specified and the tolerancing procedure can be further structured.

1.5 LIMITATIONS

Here a number of limitations for the overall project will be declared. Specific product and analysis simplifications will be declared in the methods chapter.

1.5.1 TIME AND ANALYSIS LIMITATIONS

Because of the time schedule, there are limitations to what extent analyzes can be done in multiple softwares. There are also limitations in complexity and number of furniture that can be analyzed, hence the complete product range of IKEA will not be analyzed.
Since the goal of this thesis is to demonstrate the software RD&T to IoS, it has been decided together with IoS what furniture to analyze. It has also been discussed with IoS, what kind of analyzes that would best fit their interests with the thesis.

1.5.2 REPORT AND DOCUMENTATION LIMITATIONS

The dimensions and the material structure data of the IKEA furnitures are confidential. Because of this, these can not be expressed in this report. To make up for this and an give the reader the best possible chance to follow the way of working, from method to results, the necessary dimensions used for analysis will be represented with names, pictures and descriptions instead of values.

1.5.3 SOFTWARE LIMITATIONS

The project team has not been using SolidWorks and its additional applications prior to this project. This means that the knowledge of the software and how it is implemented in the current way of working is not fully as good as the project team´s pre knowledge of RD&T. The project team will not, in the time given, be able to obtain full knowledge on how to use SolidWorks for analysis the way it is being used at IoS. The project team´s vision is to gain as much knowledge of both softwares and understand the ways of working with them to carry out analyzes with as good results as possible. This way, the project team believes they are able to make a fair benchmark between the two softwares, based on analysis results of the same product with as equal setup as possible.

1.5.4 GEOGRAPHICAL LIMITATION

There is a geographical limitation given that IoS is located in Älmhult and Chalmers University of Technology is located in Gothenburg. The project team will not be able to visit IoS for meetings with company representatives on a weekly basis. For this project the visits and meetings will have to be well planned and carried out on a number of occasions. Between these visits the necessary information will be exchanged via alternative media, such as telephone and e-mail.

2 THEORY

In this chapter the findings from the litterature study will be presented. The chapter will cover the necessary theory needed as basis for performing the analyzes of this thesis.

2.1 ROBUST DESIGN

The objective of robust design methodology is to create insensitivity to the existing sources that contributes to variation, without taking these sources away. (Bergman, B., de Mare, J. & Svensson, T., 2009) A product design is geometrically robust if it fulfills the set functional requirements and constraints, even if the geometry is affected with variation caused by manufacturing or operation. (Söderberg, R. & Lindkvist, L., 1999) The performance of a product might be affected by uncontrolled variations, also called noice. Robust design is the process of developing the perfomance of a product, while minimizing the effects of noice. (Ulrich, K.T. & Eppinger, S.D., 2012)

An important factor to control the contribution of variation is the placement of the locator points. A sensitive design contributes with higher component and assembly variation while a robust design lowers this contribution. The relationship between robustness and sensitivity can be visualized using a beam and a support stand. Figures 2.1a and 2.1b shows examples of a sensitive system and a robust system. The support stand in these examples symbolizes the locator points of the system. The robustness of the system is dependant of the placement of this support stand as it contributes to the relation between the input and the output. In Figure 2.1a the placement of the support stand contributes to higher variation as output, which results in a sensitive system. In Figure 2.1b the output variation is lower than the input variation, which results in a more robust system. (Dagman, A., Söderberg, R. & Lindkvist, L., 2006)

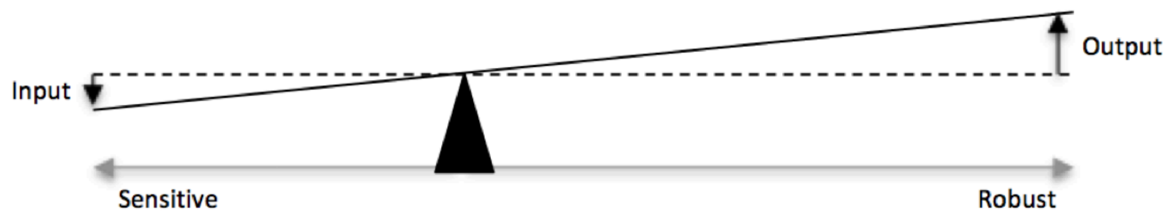


Figure 2.1a *– Example of a sensitive system*
(Inspired by Dagman, A., Söderberg, R. & Lindkvist, L., 2006)

Figure 2.1b *– Example of a robust system*
(Inspired by Dagman, A., Söderberg, R. & Lindkvist, L., 2006)

2.1.1 VARIATION

In manufacturing, variation defines how much one or more values deviate from a specified value. It is the difference between the measures on a CAD drawing and the resulting measures of a produced product. Variation can be defined between features of a single part or between features of multiple parts. (Fischer, B.R., 2011)

2.1.2 SOURCES OF VARIATION

Among multiple sources of variation, there are two major sources that should always be considered and included in a tolerance stackup.

- Specified tolerances, or other measures of part variation on a drawing
- Encountered variation in the assembly process

For the assembly process there can be contribution of variation where parts are located and/or related by external features within internal features. An example of this is a fastener within a hole. Other sources of variation can be e.g manufacturing process capability limitations, tool wear, operator error, variations in material, ambient conditions, difference in processing equipment, difference in process and poor maintenance. (Fischer, B.R., 2011)

2.1.3 DEGREES OF FREEDOM

Degrees of Freedom (DOF), is a definition of the number of axes that a rigid body is able to freely move in a three-dimensional space. It is a definition of the independent parameters that together defines the configuration of a body. An example of this is shown in Figure 2.2. Here the body is represented by a cube, placed in space with a given coordinate system. The cube can move in three dimensions by translation along the X, Y and Z axes (TX, TY, TZ), as well as change orientation by rotation around the same axes (RX, RY, RZ). This gives the cube has 6 DOF, given three types of translation and three types of rotation. (Technopedia, 2016)

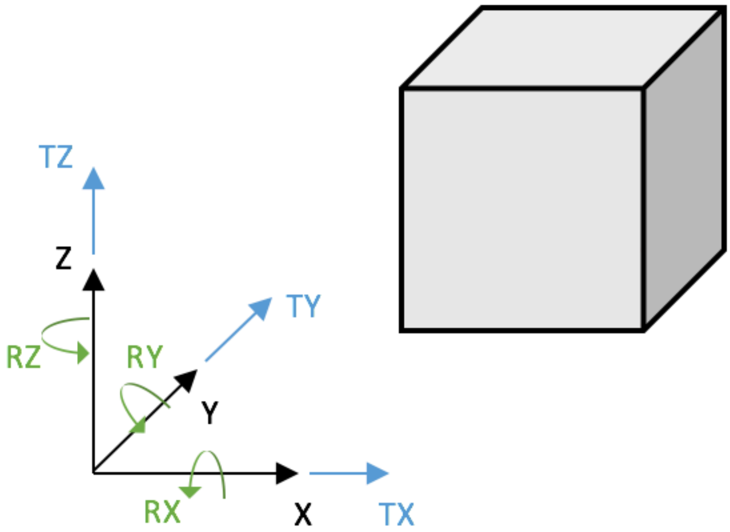


Figure 2.2 - *DOF example on a cube*

2.1.4 POSITIONING SYSTEMS

The purpose of a locating scheme is to lock a part or a subassembly to the 6 DOF in space. (Söderberg, R., Lindkvist, L. & Carlsson, J.S., 2006) To cover various industrial situations, there are multiple types of locating schemes, from which the following schemes have been used in this thesis.

2.1.4.1 THE ORTHOGONAL 3-2-1- LOCATING SCHEME

The orthogonal 3-2-1-locating scheme uses six local points of a part to mate with six target points of a corresponding part or fixture. The points are, as showed in Figure 2.3, defined as A, B and C points. The points A1, A2 and A3 form a plane which locks three DOF, TZ, RX and RY. The points B1 and B2 form a line, which locks two DOF, TY and RZ. The final point C1 locks one DOF, TX. (Söderberg, R., Lindkvist, L. & Carlsson, J.S., 2006)

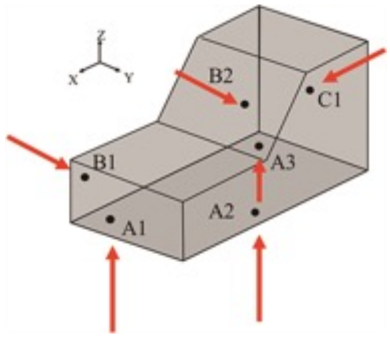


Figure 2.3 - *3-2-1 Locating scheme*
(Söderberg, R., Lindkvist, L. & Carlsson, J.S., 2006)

2.1.4.2 THE 3-POINT SYSTEM

The 3-point system is similar to the orthogonal 3-2-1 locating scheme, but here only 3 points (A1,A2 and A3) are used to lock the 6 DOF of a part or fixture. The first point A1 is used to lock 3 DOF (TZ, RX and RY), the second point A2 is used to lock 2 DOF (TY and RZ) and the third point A3 is used to lock in 1 DOF (TX). (Söderberg, R., Lindkvist, L. & Carlsson, J.S., 2006) (RD&T software manual, 2015)

2.1.5 SPLIT-LINES

When designing a product, it is of importance to analyze how to best split up the product geometry into parts while still keeping the robustness of the product. The product architecture shall be kept robust with respect to the split lines between parts. (Dagman, A. & Söderberg, R., 2003) The geometrical requirements can be evaluated by measuring the distance relation between the parts. In order to achieve an aesthetically, well balanced product structure, the distances between all edges of the product shall be equal and symmetrical. The two most common types of measures are called gap and flush. These are the types of measures that will be considered in this thesis. As shown in Figure 2.4, given two parts, gap is defined as the distance in the direction perpendicular to the normal of a common plane between the parts. Flush is defined as the distance in the direction normal to a common plane between the parts. (Dagman, A., Söderberg, R. & Lindkvist, L., 2007)

Figure 2.4 *- Gap and flush measures*

2.1.6 CONSTRAINTS

A part is considered to be overconstrained if there are more mating constraints than there are DOFs. An example of this is shown in Figure 2.5, using two pins and holes. The right picture shows a part properly constrained in x and y-directions, with the left pin being the reference pin which guides the right pin. In the left picture it is not defined which pin is the reference, making the part overconstrained.

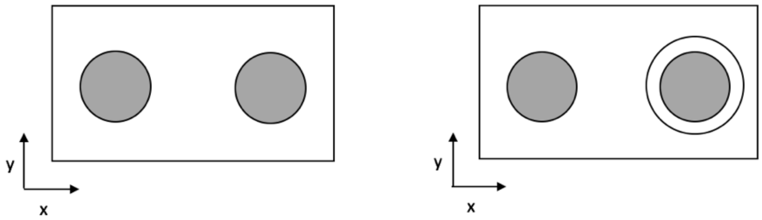


Figure 2.5 *- Example of an overconstrained (left) and properly constrained (right) part*

Overconstraining a part can give extra stability. Figure 2.6 shows a 3-2-1 and a 4-2-1 locating scheme used for the same part. In the 4-2-1 locating scheme an extra support point is added in the lower right corner of the part. By adding the extra support point the part becomes overconstrained. (Lindkvist, L., 2014)

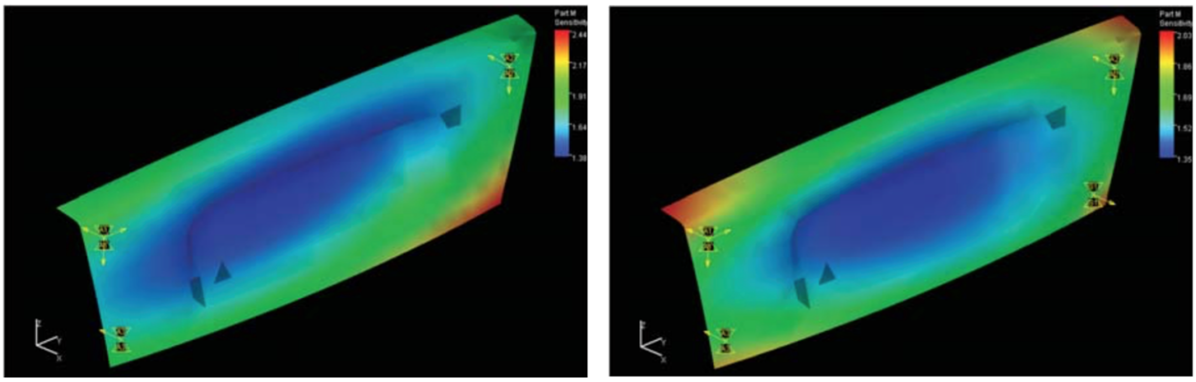


Figure 2.6 *- Examples of part sensitivity with a "3-2-1" (left) and a "4-2-1" (right) locating scheme*

2.2 TOLERANCE ANALYSIS

A tolerance specifies the allowed amount of variation from the norminal value for a feature. This may include the form, size, orientation or location of the feature. (Fischer, B.R., 2011)
When individual parts are assembled to a complete product, the total variation is the result of variation in the individual parts combined. The individual part variations contribute to the variation of critical measures for the complete product. By using a Computer Aided Tolerancing (CAT) software, the variations can be analyzed and managed to be reduced at critical measures. (Lööf, J., Hermansson, T. & Söderberg, R., 2007)

2.2.1 NON-RIGID VARIATION SIMULATION

During non-rigid analysis (also called compliant analysis) the parts are allowed to bend or deform while being positioned. Non-rigid analysis considers the material properties of parts and allows for the system to be defined with overconstrained locating schemes. (Wärmefjord, K., Söderberg, R. & Lindkvist, L., 2010) To be able to conduct a non-variation simulation using computer software such as RD&T, the parts used in the analysis needs to be meshed in a separate FEA-software before import. Meshes are used to capture-non-rigid behavior of parts during FEA (Wärmefjord, K., Söderberg, R. & Lindkvist, L., 2008)

Direct Monte Carlo (DMC) simulation (further described in chapter 2.2.5) in combination with FEA is a common way to conduct variation simulation of non-rigid parts. DMC is used for performing tolerance stack-up and predict part variation of the final assemby. FEA is used to capture non-rigid behavior of parts, such as bending during assembly due to errors in part geometries and fixtures. (Jareteg, C. et. al., 2014)

2.2.2 MESH

Mesh generation is defined as the process of generating a polyhedral or polygonal mesh to represent a digital geometry. It is a commonly used in FEA, where the meshes are imported from outer Computer-Aided Design-software (CAD-Software). Meshes can be categorized as 1D, 2D and 3D meshes. 1D meshes are defined by a number of nodes positioned on a line or a curve to create a mesh. 2D meshes, are also called surface mesh or shell element, uses nodes and triangular or quadratical elements to build mesh. 2D mesh makes it possible to add more than one material to each part. Here it is possible to divide a part into a number of material sets and thickness plies. 3D mesh also refers to solid mesh where nodes and hexahedra, pyramids and tetrathedra elements are used to build mesh. For 3D mesh each part is being considered as being made out of one material. (Edelsbrunner, H., 2001) The two types of mesh considered for this thesis are solid mesh and surface mesh.

2.2.3 GD&T – GEOMETRIC DIMENSIONING & TOLERANCING

Geometric Dimensioning & Tolerancing (GD&T) is a symbolic language which is used to specify the form, size, shape, orientation and location of features on a part. GD&T is a design tool and reflects the actual relationship between mating parts. It is used as a reminder for the designer to consider fit and function of each feature of a part. (Cogorno, G.R., 2011)

2.2.4 DIMENSIONAL CHAINS

A dimensional chain is the connection of interdependent dimensions, creating a closed circuit. The dimensions can specify the mutual positioning of features on one single part or between several parts in an assembly. A dimensional chain is including separate input dimensions, called partial components and a resulting dimension, called closed component. In Figure 2.7 the partial components are named A-G and the closed component is named Z. The closed component Z is the result combining the partial components A-G in manufacturing or during assembly.

There are three types of dimensional chains, based on the mutual position of the individual components.

- 1D, Linear chains - Chains that only include parallel dimensions.
- 2D, Two-dimensional chains - Chains that include dimensions in one or more parallel planes.
- 3D, three-dimensional chains - Chains that include dimensions that lies in non-parallel planes. (MITCalc, 2016)

For the softwares used in this thesis, SolidWorks TolAnalyst calculates and stacks up 1D at a time during analysis while RD&T calculates and simultaniously stacks up in 3D. (RD&T Technology, 2016) (SolidWorks, 2016)

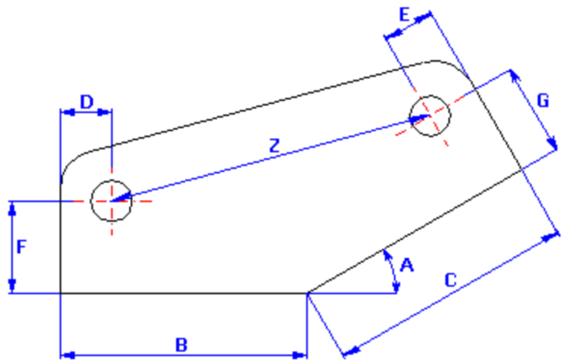


***Figure 2.7** – Dimensional 2-D chain example*
(MITCalc, 2016)

2.2.5 MONTE CARLO SIMULATION

Monte Carlo simulation is a tolerance stack-up method based on random numbers to simulate the randomness that can occur in reality. For each sample run a random value is chosen for each dimension in the stack-up chain. These values are chosen to fit the statistical distribution and the dimensions are combined according to the stack-up equation. By running this analysis multiple times the probability distribution for the assembly dimension is built up. Higher number of iterations increases the probability of results more accurate and closer to reality. A drawback of this is that the more iterations runned, the longer the simulation time will be. Monte Carlo simulation can give reliable results since the method is considering the effects of non-linear stack-up equations and also allow for non-normally distributed dimensions. This gives the method good control over the variations that occur in the process. (Marrs, J., 2012)

2.2.6 WORST-CASE METHOD

The worst-case method is done in two steps. First the maximum assembly dimension is calculated followed by the minimum assembly dimension according to Equation 1. The result is the maximum possible contribution to the final result based on each individual source of variation.

$$D \pm t = (D_1 + D_2 + D_3) + (t_1 + t_2 + t_3) \tag{1}$$

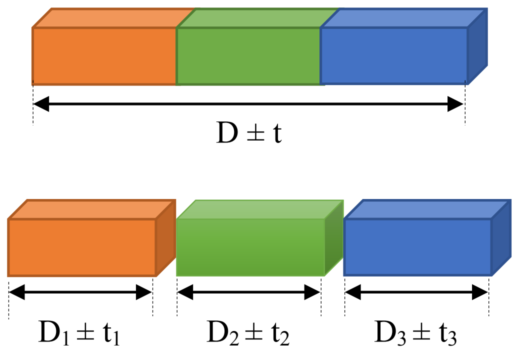


Figure 2.8 *- Worst-Case dimension and tolerance stack-up example*

Figure 2.8 shows an example of worst-case tolerance. Here the maximum assembly dimension is $(D_1 + D_2 + D_3) + (t_1 + t_2 + t_3)$ and the minimum assembly dimension is $(D_1 + D_2 + D_3) - (t_1 + t_2 + t_3)$. The maximum assembly dimension is obtained by adding the maximum value of all the positive contributors and subtracting the minimum of all negative contributors. The same procedure is is used when calculating the minimum assembly dimension, but now the minimum value of all the negative contributors are added and subtracted with all the maximum values of the positive contributors. This method is fast but simplistic, which may not give the most accurate results. However, it is good when the user wants to lower the risks. (Marrs, J., 2012)

2.2.7 ROOT SUM SQUARED

The Root Sum Squared (RSS) method is a statistical method which, as shown in Equation 2, adds the squares of all the tolerances in the tolerance stackup and then gives the square root of this addition as result. (Fischer, B.R., 2011)

$$RSS\ Tolerance = \sqrt{{T_1}^2 + {T_2}^2 + \cdots + {T_n}^2} \tag{2}$$

$$n = Number\ of\ tolerances\ in\ the\ tolerance\ stack - up$$

2.2.8 PROCESS CAPABILITY INDICES (PCIs)

In this segment the different ways of defining the indices on what quality processes are capable of producing will be presented. The capability indices are based on assumption of normal distribution.

2.2.8.1 PROCESS CAPABILITY (C_p)

C_p is an index that considers the overall variability of the process relative to the tolerance of manufacturing. C_p considers the index between the upper specification limit (USL) and the lower specification limit (LSL) of the process and divides this range with six times the process standard deviation value , as showed in Equation 3. A graphical example of this can be seen in Figure 2.9.

$$C_p = \frac{USL - LSL}{6\sigma} \tag{3}$$

A drawback with the C_p index is that it considers the potential of a process according to the process spread without considering the mean of the process. (Chang, Y.C., 2008)

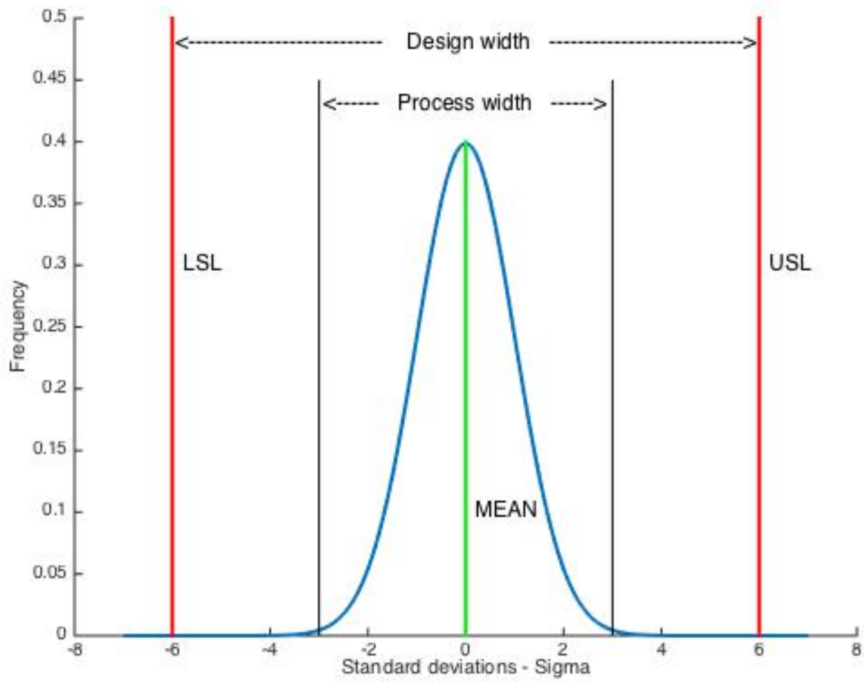


Figure 2.9 *- Example of process capability using C_p*
Matlab code for creating figure is attached in Appendix C

2.2.8.2 PROCESS CAPABILITY INDEX (C_{pk})

If the process target value T is the midpoint of the specification interval (LSL, USL), the process have a symmetric tolerance; $T = M = \frac{USL+LSL}{2}$. If the mean value is shifted and not centered between the specification limits, the C_p index is overestimating the process capability. In this situation the C_{pk} index, as shown in Equation 4, can be used to estimate process capability. (Pearn, W.L., 1998) (Chang, Y.C., 2008) A graphical example of this can be seen in Figure 2.10.

$$C_{pk} = min\left\{\frac{USL-\mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\} = \frac{d-|\mu - M|}{3\sigma} \tag{4}$$

μ = Process mean, σ = Process standard deviation, $d = \frac{USL-LSL}{2}$

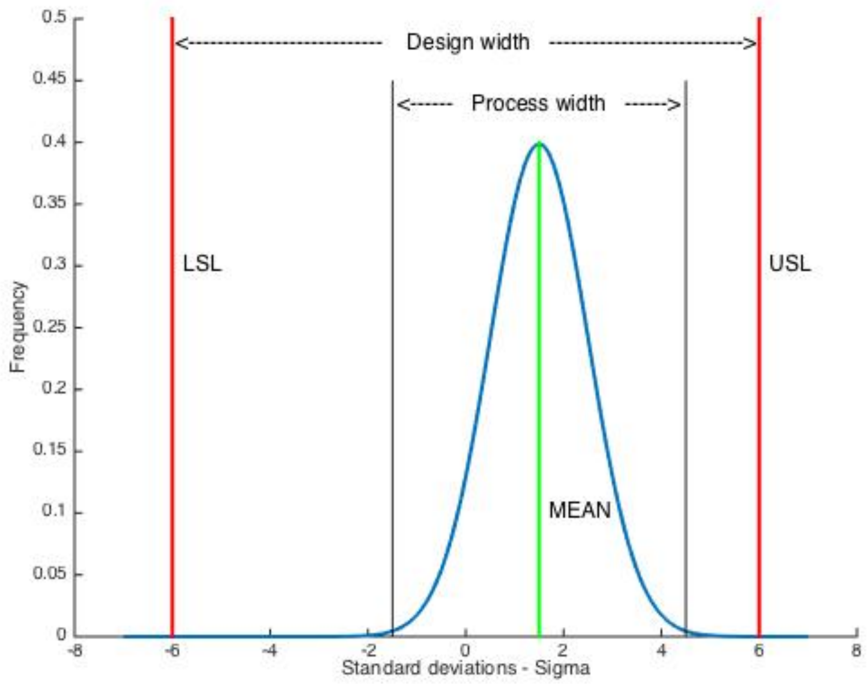


Figure 2.10 *- Example of process capability using C_{pk}*
Matlab code for creating figure is attached in Appendix C

2.3 RD&T

RD&T is a software package developed by RD&T Technology AB. It is a tool used for statistical variation simulation, based on digital models. RD&T allows simulation of manufacturing and assembly deformations of a product in the early phase of the product realization loop. RD&T supports the whole geometrical assurance process throughout a product realization loop, from early concept design phase to pre-production and production phase. There are two strong focuses of RD&T software. One is robust design of the concept, which focuses on making the design concept as non-sensitive to variation as possible. The other is predicting final variation in the products critical areas, which aims to optimizing the tolerance and lower the manufacturing costs. To assure geometrical robustness, RD&T uses the following functions;

- ***Stability analysis***
  By using the stability analysis, the robustness of the design and the assembly concept can be analyzed and evaluated in the early design phases. The stability analysis is used to determine the geometrical sensitivity based on the position of the locators. With respect to critical areas or overall sensitivity the locator positions can then be manually or automatically optimized.

- ***Statistical variation simulation***
  To statistically analyze variation while capturing all the 3D effects and interactions for complex assemblies, RD&T uses Monte Carlo simulation. RD&T also allows Non-Rigid analysis because of its integrated FEA solver. Because of this, the effects of the material properties can be included in the analysis, allowing parts to bend or deform during assembly. The FEA module also allow analysis and optimization of assembly, welding and clamping order. This way the variation can be minimized.

- ***High-end visualization***
  RD&T includes a show-room where the variation effects can be vizualised with high degree of realism. This is done by adding lightening, shadows, material properties and texture to the model. RD&T also includes interfaces to some of the market leading visualization software packages. Because of this the geometrical variation can be visualized before production and unnecessary changes late in the process can be avoided.

- ***Geometry assurance process and documentation***
  The RD&T process is generic and is suitable for a variety of industries that are producing physical products. RD&T is a software that supports the geometry process from early requirement definition, through optimization of the locators, variation analysis, matching and trimming, with full engineering documentation and drawings. (RD&T, 2016)

2.4 SOLIDWORKS

SolidWorks is a solid modeling computer-aided design (CAD) and computer-aided engineering (CAE) software package used to create and build parts, assemblies and drawings. It can be used for design and analysis, giving the user a possibility to model in 2D and 3D.

2.4.1 DIMXPERT

DimXpert is a set of tools in SolidWorks, used to apply dimensions and tolerances on parts. By using DimXpert, all the manufacturing features like pockets, patterns and slots can be fully-defined in drawings. The DimXpert toolbar offers a number of tools which can be used for either auto dimensioning or manual dimensioning. By using a status command in DimXpert, the user can be notified on current tolerancing status by observing a resulting color coded part. Here green indicates that the part is fully dimensioned and constrained, yellow indicates that the part is partly dimensioned and constrained and grey (default color) indicates that the part is not dimensioned or constrained. (Planchard, D., 2015) An example of this can be seen in Figure 2.11, which is showing one of the Valje side panels dimensioned and toleranced using DimXpert.

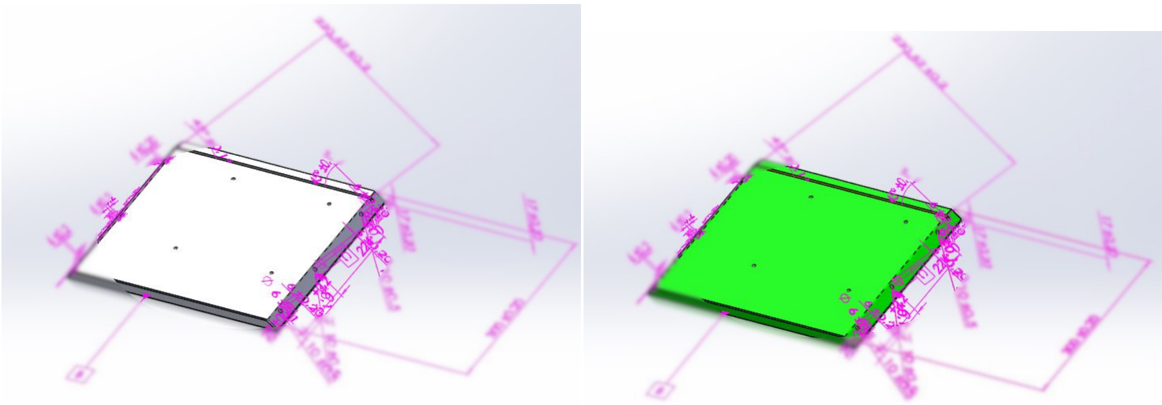


***Figure 2.11**- Valje side panel dimensioned and toleranced using DimXpert*
Regular view (left) and control view (right)

2.4.2 TOLANALYST

TolAnalyst is an application available in the premium version of SolidWorks. It is used to analyze tolerances and to determine the part and assembly effects of the dimensions and tolerances that are set using DimXpert. TolAnalyst is used to leverage the data for stack-up analysis. The TolAnalyst analysis procedure can be divided up into 4 steps; measurement, assembly sequence, assembly constraints and analysis results.

- ***Measurement***
  The user creates a linear measurement between two DimXpert objects at location of interest.

- ***Assembly sequence***
  The assembly sequence is determined to establish a tolerance chain between the measurement features. The assembly sequence is a simplified assembly which shall include at least the parts of the product which are necessary to establish a tolerance chain between the two chosen measurement features.

- ***Assembly constraints***
  For each part of the assembly, it shall be defined how the part is placed or constrained. The constraints are placed in sequence, which can affect the end result.

- ***Analysis results***
  The results given are minimum and maximum worst case tolerance stacks and Root Sum Squared (RSS) minimum and maximum. (Planchard, D., 2015)

3 THE PRODUCT – VALJE

The product analyzed in this thesis was chosen based on suggestions from IoS. Out of two suggested alternatives the wall mounted dresser "Valje" was chosen for analysis (see Figure 3.1). Analyzing this product was believed to be a good way to show IoS what the software RD&T is capable of performing and how it could be implemented in their way of working. Another reason for Valje being chosen is because it is built up by using multiple concepts that are currently used and further planned to be exposed in bigger scale in future IKEA furnitures.

Figure 3.1 - *Valje dresser*
(IKEA.com, 2016)

3.1 PRODUCT DESCRIPTION

Valje is a wall mounted dresser, built up by a frame consisting of top, bottom, back and two side panels. In this frame two drawers are mounted. These drawers can be opened and closed using a springed sliding mechanism activated by pushing the drawer. The drawer is also locked in closed position by pushing the drawer after closing.

The dresser is partly assembled using the new type of interface that IoS calls "wedge dowel". The frame panels are assembled to each other by having grooved pins slided and locked into position in corresponding milled keyholes. For each of the frame side panels there are three wooden grooved pins on each side to be assembled against milled keyholes of top and bottom panels. This gives a total of six grooved pins on each frame side panel and twelve grooved pins in total for the frame. Corresponding to the pins there are six milled keyholes on both top and bottom panels, giving it a total of twelve milled keyholes for the frame (See Figure 3.2).

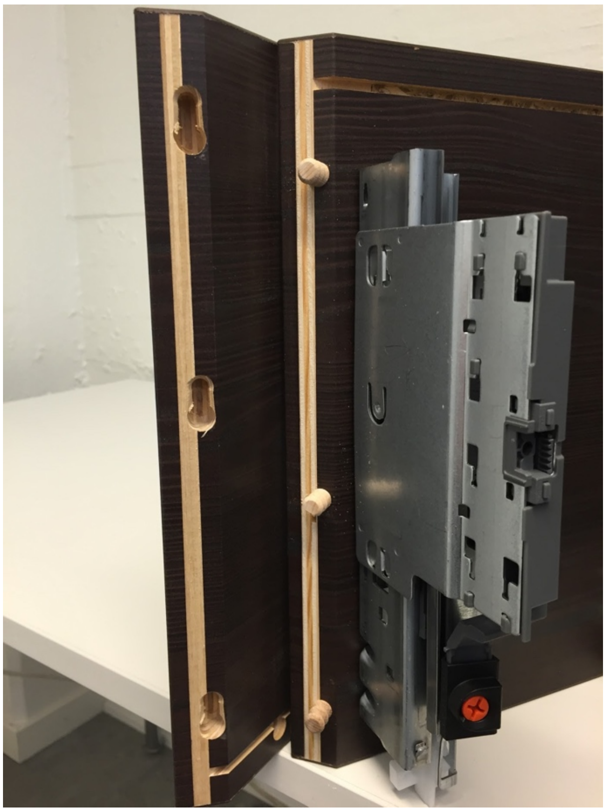


***Figure 3.2** – 3 wedge dowel pairs. Located in one corner of the Valje frame.*

The drawers of Valje are assembled similarly, but here the grooved wedge dowel pins are made out of plastic and there are just 4 wedge dowel pairs used. These are used to assemble the front panel of the drawer to the drawer side panels with two wedge dowel pairs on each side.

For this thesis the frame, built up by top, bottom and the two side panels, has been assembled and analyzed. This assembly has been analyzed for variation, contribution, stability and stress.

3.2 ASSEMBLY SEQUENCE

Because of the frame of Valje having equal assembly interfaces in each corner, there are 16 alternative assembly sequences for the four panels (as listed in Table 3.1a). Two additional assembly sequences can also be added if it is considered that the panels can be assembled two by two into subassemblies followed by having the subassemblies assembled as a full frame (as listed in Table 3.1b.

***Table 3.1a** - General assembly sequences*

Assembly no. / Part order no.	1	2	3	4
1	Left side panel	Top panel	Bottom panel	Right side panel
2	Left side panel	Bottom panel	Top panel	Right side panel
3	Left side panel	Top panel	Right side panel	Bottom panel
4	Left side panel	Bottom panel	Right side panel	Top panel
5	Right side panel	Top panel	Bottom panel	Left side panel
6	Right side panel	Bottom panel	Top panel	Left side panel
7	Right side panel	Top panel	Left side panel	Bottom panel
8	Right side panel	Bottom panel	Left side panel	Top panel
9	Top panel	Left side panel	Right side panel	Bottom panel
10	Top panel	Right side panel	Left side panel	Bottom panel
11	Top panel	Left side panel	Bottom panel	Right side panel
12	Top panel	Right side panel	Bottom panel	Left side panel
13	Bottom panel	Left side panel	Right side panel	Top panel
14	Bottom panel	Right side panel	Left side panel	Top panel
15	Bottom panel	Left side panel	Top panel	Right side panel
16	Bottom panel	Right side panel	Top panel	Left side panel

***Table 3.1b** - Additional assembly sequences*

Assembly no. / Part order no.	1		2
17	Left side panel / Top panel	Right side panel/ Bottom panel	Full frame
18	Left side panel / Bottom panel	Right side panel/ Top panel	Full frame

To neglect the variation caused by assembly sequence, the project team, in agreement with representatives of IoS and Wingquist Laboratory, decided to use the assembly sequence suggested in the user assembly manual for product Valje as the assembly sequence for analysis. This assembly sequence is described as the second sequence of Table 3.1a; where the left side panel is positioned and used as ground part. Then the bottom panel is assembled on to this panel followed by the top panel and finally the right side panel is assembled to the top and bottom panels, closing the frame and finalizing the full assembly.

3.3 WEDGE DOWEL CONSTRAINTS

For the wedge dowel interface, the first grooved pin and corresponding milled keyhole of each frame corner, closest to the front of the frame, is considered to be the guiding pair. The second and third pin and keyhole pairs follow the motion of the first pair and are adjusted by set tolerances (see Figure 3.3). This gives a system that is not overconstrained. It might give a result where the second and third pin and keyhole pairs does not fully align and click in position, but the gripping here is still considered to be strong enough to give a good assembly.

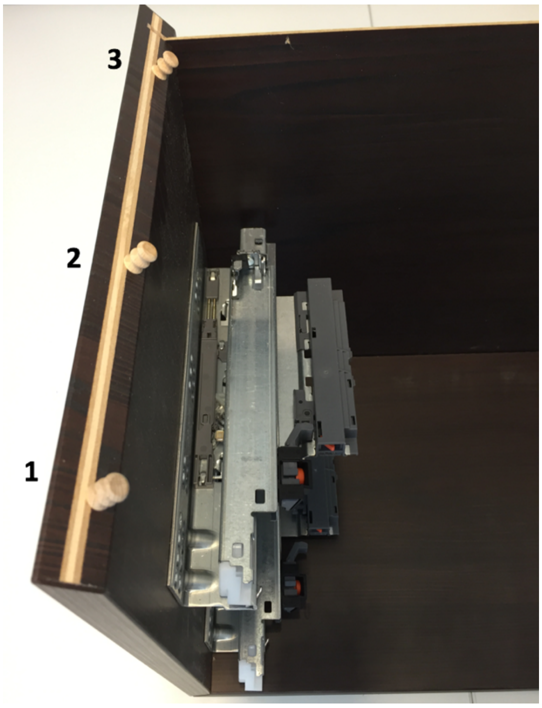


Figure 3.3 *- Guidance and following wedge dowel grooved pins*

4 METHOD

In this chapter, the methodology used during this master thesis project will be presented with an overall description of each step. The used methodology can basically be divided into two parts, overall methodology and a detailed technique methodology. Overall methodology describes how the project team organized and conducted the various steps of the project, while the technique methodology describes in deep how the modelling was done with respect to performing simulations for the IKEA furniture Valje, using the softwares RD&T and SolidWorks.

4.1 PROJECT METHOD

The overall project methodology describes how the project team scheduled and managed routine of the project in order to create conditions for reaching the best result possible. It can be divided and categorized as follows.

- Literature and software study
- Company visits and meetings with experts at Chalmers
- Progress meetings (4 times)
- Manual assembly of the product Valje
- Modelling and analysis in RD&T (Rigid and Non-rigid) and Solidworks (Rigid)
- Report (documentation, report, presentation)

- ***Literature and software study***

  To get a good understanding of the area a literature study, including theory and previous findings in similar cases, was conducted in the startup phase of the project. This continued in varying scale throughout the remainder of the project as well, when extra theory was needed.

  The project group was familiar with the software RD&T and had used it multiple times prior to the project. To refresh the knowledge of the software the project group did a number of exercises and played around with the software and its functions.

  To understand the software SolidWorks, including DimXpert and TolAnalyst, the project group studied walkthrough videos and tutorials online and adapted the theory and methods learned into the analysis of Valje.

- ***Company visits and meetings with experts at Chalmers***
  This project has included a number of visits to the IoS headquarters in Älmhult Sweden. These visits has been informative and important for the thesis as they have given a bigger picture of the reason and need for this thesis and the possible results that might come out of implementing alternative ways of working. During the visits representants of IoS has informed about the company and their way of working today. Meetings with representants of general tolerancing using SolidWorks and representants working specifically with the product chosen for analysis has been of importance when building the analysis set in RD&T. It has been of importance to have the general analysis setup as close to the current one or better to create the best conditions possible for a good and fair comparison between the analysis methods and softwares.

- ***Manual assembly of the product***
  To fully understand how the product is built up, a copy of Valje was bought and assembled. This way the physical copy of the product worked as a complement to the drawings since the product could be disassembled and inspected from every angle.

- ***Progress meetings***
  To keep the representants of Wingquist and IKEA updated on the progress of the thesis project, four progress meetings were scheduled and conducted. During these meetings the project group presented the findings at current state of the project and then a discussion followed regarding the current result as well as how to proceed until the next meeting.

- ***Modelling and analysis in RD&T rigid and non-rigid) and SolidWorks (rigid)***
  The project group did various modeling and analyzed the product "Valje" in both softwares RD&T and SolidWorks. This was done in order to later be able to compare the two softwares, how to use them and the results obtained using them. A step-by-step description of these procedures will be presented in chapter 4.2

- ***Report (documentation, report and presentation)***
  The preparations, courses of action and results of each step of this thesis work has been documented. The results of this is presented in this master thesis report and used as a basis for oral presentations at Chalmers and IoS.

4.2 TECHNIQUE METHOD

In this chapter, the methods used for analysis and simulation of the product Valje will be presented. The variation simulation is conducted using RD&T for rigid and non-rigid simulation and SolidWorks for rigid simulation.

4.2.1 PRODUCT AND ANALYSIS SIMPLIFICATIONS

As a part of the method, preparing for simulation, some product and analysis simplifications were considered. These simplifications were implemented in order to achieve as accurate and comparable results as possible.

- ***Analysis done only on frame assembly of the dresser.***

  When analysing the dresser, only the frame assembly of the top, bottom and two side panels were considered (as shown in Figure 4.1). The back panel drawers and the drawer sliding mechanism were neglected. The back panel is not attached to anything in the final assembly. It is only fitted and positioned in the assembly by grooves in the surrounding frame panels, which gives that this panel does not contribute to the variation of the rest of the frame. Because of this the back panel was neglected as well. The drawers were neglected because the dimensions of the sliding mechanism for the drawers is confidential. Because of this there were no CAD-files to obtain for these parts and it was not possible for the project team to model any on their own. The lack of models for the sliding mechanism would result in an assembly where the drawers are floating in mid air inside the frame of the dresser. Because of the drawers not being connected to the frame, the drawers and the frame would be independent of each other during analysis and the result would not be correct. Because of this the drawers were neglected. Another reason for the drawers being neglected was because the drawers partly use the same fastener interface as the frame. Because of this the effect of using this kind of fasteners and how to analyse them using RD&T could be displayed to IoS by performing in deep analysis on the frame assembly instead. Also, the position of the drawers can be adjusted by the user after assembing the final product. There are settings included in the sliding mechanism, giving the customer the possibillity to manually tilt the drawers to adjust gaps and flushes.

Figure 4.1 *- Valje frame*

- ***Meshing of the frame panels.***

  All the panels of the frame was meshed as a solid mesh with 6 mm mesh size. The reason for choosing a mesh size of 6 mm was because of the RD&T manual stating that the analysis results would not give any better results with a mesh size smaller than 5 mm. Any mesh size smaller than 5 mm would result in analysis results equal to a mesh size of 5 mm. The mesh size was also chosen based on the height of the 45 degree surfaces (direction pointed out by the green arrow in Figure 4.2). This measure is equally divided by 6 mm, and because of this, choosing a mesh size of 6 mm placed a layer of nodes in midheight of the 45 degree surfaces. This made it easier to position the fasteners resembling the wedge dowels. The positioning of the fasteners, based on the width of the 45 degree surface (direction pointed out by the red arrow in figure 4.2) was simplified to be the measures equally divided with 6 mm closest to the actual measures defined on the product drawings.

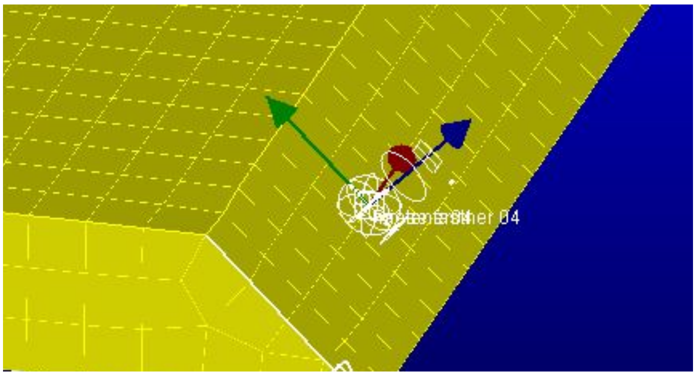


Figure 4.2 *– Mesh and mesh directions*

- ***Usage of fasteners instead of wedge dowel CAD-parts***

  Instead of using toleranced CAD-versions of the wedge dowel grooved pin and milled keyhole pair, the RD&T function ”fastener” was used instead. By modifying and tolerancing these fasteners in the RD&T fastener options tab, they could be used to represent the wedge dowels. There are great advantages in using a modified fastener in this case. It is time saving since the user just have to point and click where the fastener is supposed to be located and then modify the predefined settings to make the fastener fit the needs for the specific case. The fasteners that are supposed to have the same specifics can then be linked with each other, giving the user the possibility of adjusting all these linked fasteners at the same time by adjusting one of them.

4.2.2 RD&T RIGID SIMULATION

When a rigid simulation is conducted, objects are treated as solid and can not be deformed when loaded. The material properties of the assembly is excluded. The general procedures of performing a rigid simulation in RD&T can be described as follows.

- Import CAD file into RD&T environment
- Define assembly strategy
- Define locating scheme(s)
- Add tolerance(s)
- Create measure(s)
- Analyze
  - Variation, stability and contribution analysis

- ***Import CAD file into RD&T environment***
  Prior to starting a simulation, a CAD-file should be prepared. The file formats that are accepted for rigid simulation in RD&T includes IGES, STL, VRML 1.0/2.0 and JT. Since RD&T has a powerful modeling engine, it is possible to model a part within the RD&T environment. This is however not recommended as geometries in modern industry tend to be quite complex and would therefore take long time to model. It may also not be a good option if the target part is of high complexity.

  When importing an assembly into RD&T, there is a risk that the positioning of the parts becomes disordered. Because of this, it is of importance to keep the parts positioned correctly in the CAD software when exporting. If this is done, the parts will keep their position in RD&T when importing, which will make prework in RD&T easier. Also the accuracy of simulation results will be increased. An instruction for how to import CAD-files into RD&T while keeping the parts positioned is presented in Appendix A.

  For this master thesis the CAD parts offered by IKEA for the product Valje had been created using SolidWorks. These files were then converted into VRML format and imported to RD&T.

- ***Define assembly strategy***
  Once the CAD-files are converted and imported into RD&T, the assembly strategy should be considered. The assembly strategy defines how the parts are assembled together and in which order. In the early design phase, the assembly strategy is not fixed. Normally it is possible to assemble a product in multiple ways using various assembly orders. In RD&T there is a function called "alternate assembly" which can be used to quickly switch between a number of defined assembly strategies. This makes it easier to keep track of the different assembly strategies and compare them against each other.

  As stated earlier, the chosen assembly strategy for the frame of Valje was to start by putting the left side panel in position. After this the bottom and top panels are assembled to the left side panel in sequences followed by assembling the right side panel on to the top and bottom panels as the final step.

- ***Define locating scheme(s)***
  Locating schemes are one of the main parameters of variation. As described in the theory chapter, the purpose of a locating scheme is to lock a parts position in space. For this simulation method a combination of 3-2-1-positioning and 3-points positioning was used.

  When assembling the frame of Valje, the previously described function ”assembly sequence" was used. By using this function, two simulation loops for each assembly step was used and a dependency loop could be avoided. The definition of a dependency loop is when part A is assembled onto part B followed by part B being assembled onto part A later on. (RD&T software manual, 2015) If there is a dependency loop, RD&T can not simulate. This gives that if each panel for the Valje frame was determined to have one side as local and the opposite side as target for another panel when assembling, a dependency loop would occur because of each corner being dependant of each other.

For this thesis, when assembling the frame of Valje, if top or bottom panel is assembled onto one of the side panels, the assembled end will be quite stable while the corresponding side of the top or bottom panel will be exposed to a lot of variation (see Appendix B).

As stated, during final rigid variation simulation, two simulation loops were used for each assembly step. In first step the bottom panel was locked in space and assembled against the left side panel by using a 3-points positioning scheme. Here A1 and A2 was positioned on hole center of the outer holes (hole 1 and hole 3) and an addiditonal point, ”H”, was used as A3. ”H” was used to resemble a hand holding the part while assembling. The same procedure was done for the top panel, assembled against the left side panel. The locating scheme for this assembly is shown in Figure 4.3 with points highlighted in black. The right side was assembled against the top and bottom panels by using a 3-points positioning scheme as shown in Figure 4.3, highlighted in green. For the second step the top and bottom panels were assembled by using the same 3-points positioning schemes as defined in step one, but moving the point ”H” (A3) to the step 1 A3 position of the right side panel, as shown in Figure 4.3 with a white arrow. By using two simulation loops the dependency loop could be prevented.

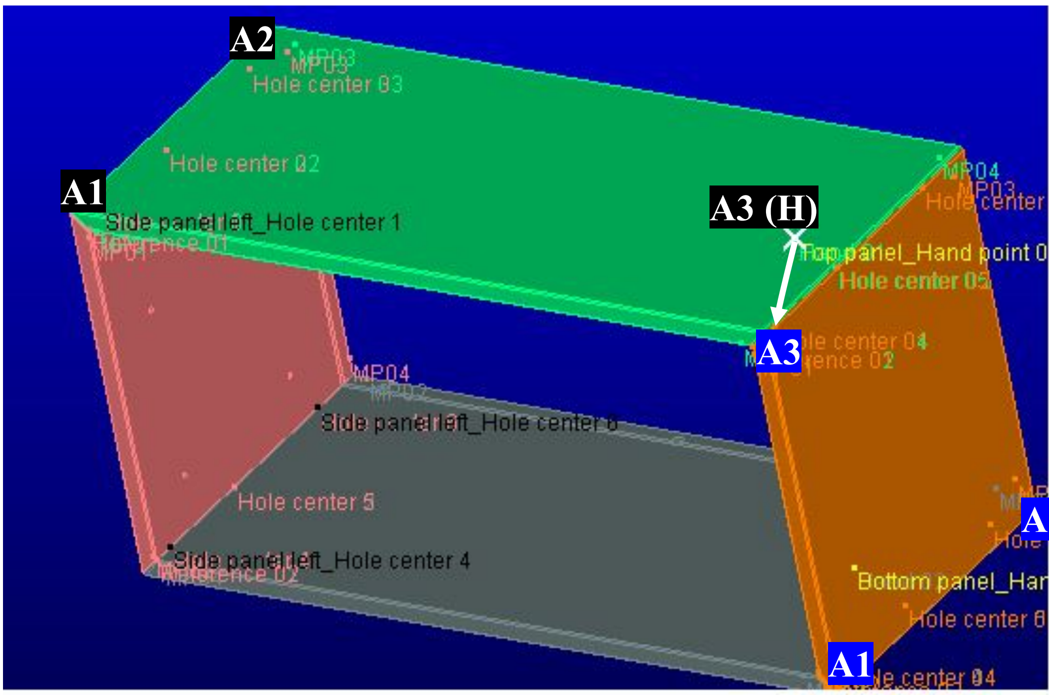


Figure 4.3 *– Locating schemes for top (black highlight) and right side (blue highlight) panels for step 1. Arrow indicating movement of H for step 2.*

- ***Add tolerance(s)***
  Tolerances are another main parameter of variation. These are usually defined on locator points and points used for measuring. All the tolerances used for this thesis were defined as on IoS 2D-drawings of Valje and documents specifying general tolerances for the product family.

- ***Add measure(s)***
  Measures are defined by the user on points or between points, in critical or interesting areas. RD&T offers several types of measures, e.g. point self, point-to-point, positioning, line-self etc. The majority of the measures defined for this kind of simulation in this thesis was of type gap and flush. For the RD&T simulations the measures listed in Table 4.1 were created.

***Table 4.1** – Measures defined for simulation in RD&T*

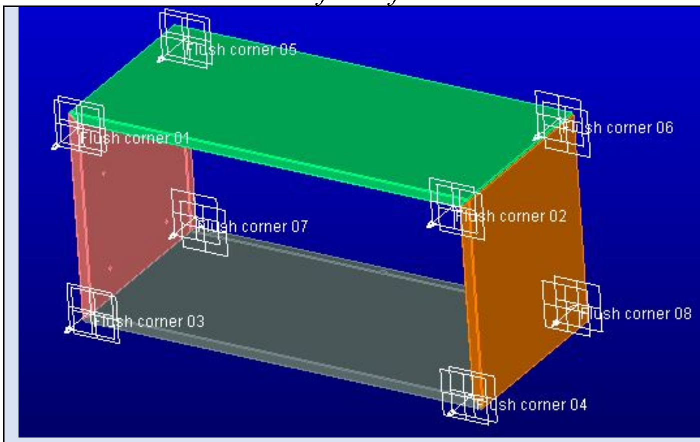
<table>
<tr><td rowspan="2">

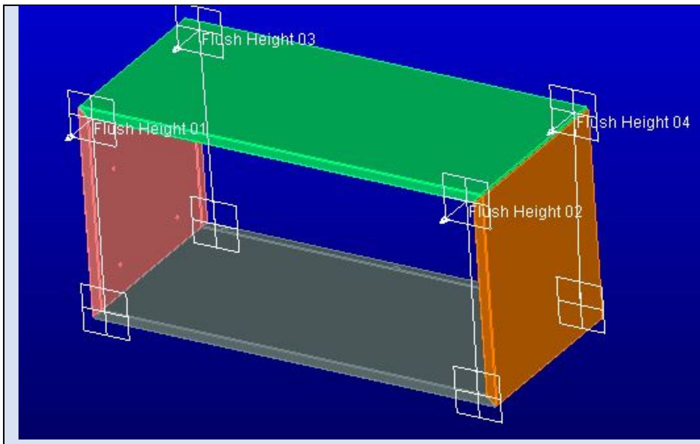
Figure 4.5 – Corner flush measures</td><td>8 corner flush measures</td></tr>
<tr><td>For analysis of flush between the corner panels, 8 corner flush measures, named ”Flush corner” 01-08 were created. These measures determine the distance between two planes in the direction normal to the common plane. The position and orientation of these measures are shown in Figure 4.5.</td></tr>
<tr><td rowspan="2">

Figure 4.6 – Height flush measures</td><td>4 height flush measures</td></tr>
<tr><td>For analysis of flush between the top and bottom panels, 4 flush measures named ”Flush Height” 01-04 were created. These measures determine the distance between two planes in the direction normal to the common plane. The position and orientation of these measures are shown in Figure 4.6.</td></tr>
</table>

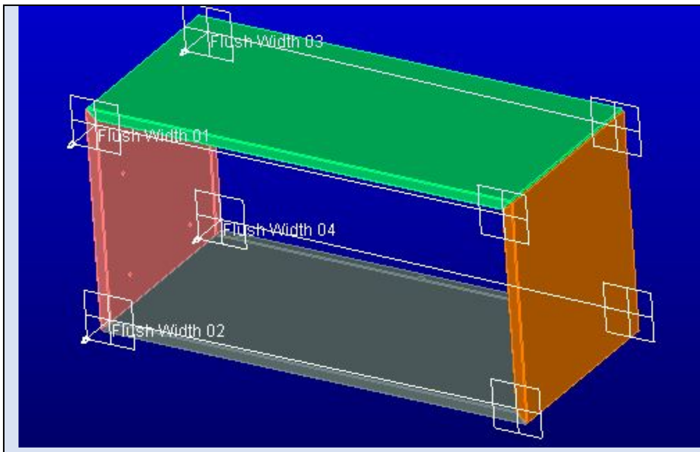


***Figure 4.7** – Width flush measures*

4 width flush measures

For analysis of flush between the left and right side panels, 4 flush measures named ”Flush Width” 01-04 were created. These measures determine the distance between two planes in the direction normal to the common plane. The position and orientation of these measures are shown in Figure 4.7.

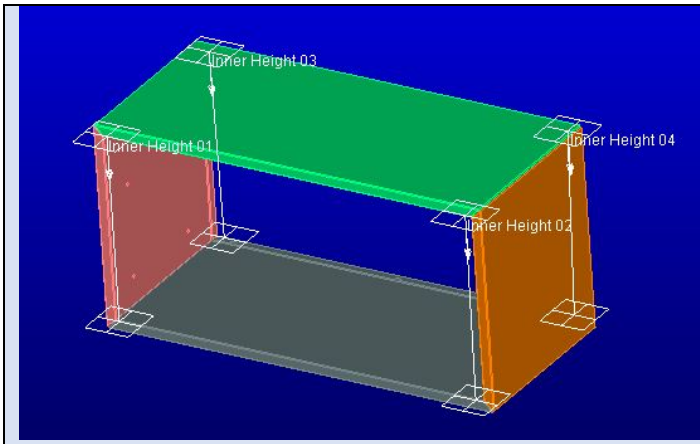


***Figure 4.8** – Inner height measures*

4 inner height measures

For analysis of inner height, 4 gap measures named ”Inner Height” 01-04 were created. These measures define the distance in vertical direction between the top and bottom panels. The position and orientation of these measures are shown in Figure 4.8.

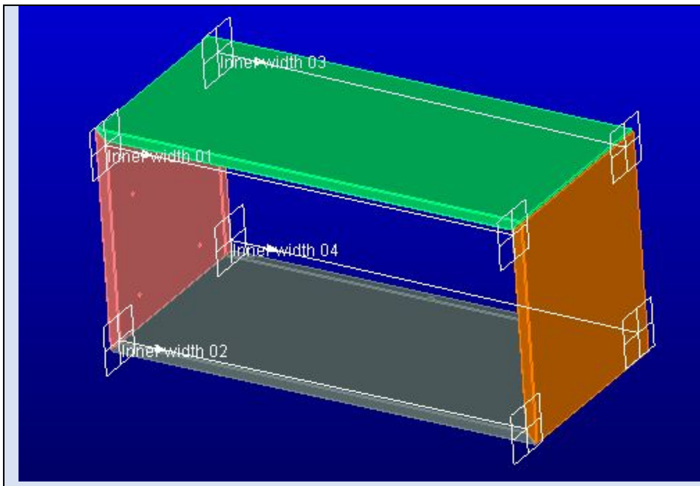


***Figure 4.9** – Inner width measures*

4 inner width measures

For analysis of inner width, 4 gap measures named ”Inner Width” 01-04 were created. These measures define the distance in horizontal direction between the left and right side panels. The position and orientation of these measures are shown in Figure 4.9.

- ***Analyze***
  Stability, variation and contribution vere analyzed. Stability simulation illustrates the robustness of the assembly concept. Monte Carlo based statistical variation simulation was used to predict the final variation of the assembly. Finally the contribution simulation results in a ranked list of tolerances contributing to variation.

4.2.3 RD&T NON-RIGID SIMULATION

As mentioned, RD&T non-rigid simulation makes it possible to overconstrain the included parts and take material properties into consideration. In non-rigid simulation the geometries are represented by solid or surface meshes. The locator points and measure points are defined using the mesh nodes. For this thesis both solid and surface mesh models were created. The solid mesh model can simulate simplified materials, assumed as isotropic material, while the surface mesh model can simulate more complex materials, like laminated material and materials with several different layers and sets.

- ***Import mesh file(s) to RD&T***
  Since non-rigid simulation uses meshes to represent geometries, the first thing to consider before setting up the analyses is to create and import the mesh to RD&T. For this thesis, solid mesh was created using CATIA V5 advanced workbench. Here a mesh element size of 6 mm was used. The surface mesh sets were generated using Abaqus/CAE. More information on how to create surface mesh sets is attached in Appendix B.

- ***Define materials***
  In RD&T, materials are defined by entering material properties in the ”*compliance* ” tab. For solid mesh it is only possible to model isotropic material and it is only possible to apply one material to each part.
  With surface mesh it is possible to analyze IKEA´s new material structure, since this is consistant of several sets and plies. For this, the parts were defined as composite parts in the RD&T ”*compliance*” tab and the material properties were defined with composite properties. All the data for this was given by IKEA.

- ***Define locating scheme(s)***
  In this non-rigid variation simulation, the parts were assembled using the built in fastener function of RD&T. 12 fasteners were defined, 3 in each corner of the frame. These fasteners were used to represent the 12 wedge dowel pairs during analysis.

- ***Adapt and adjust fasteners***
  For RD&T non-rigid stress analysis, the fasteners were modelled to resemble an applied pulling force between the parts in each corner of the frame. This was done by moving the contact point of the fastener from the interfacing surface between the parts to a position inside the counterpart. An example of this is shown in Figure 4.10, where the fastener (wedge dowel grooved pin) is located on the left side panel, marked with an ”L” and the counterpart of the fastener (the wedge dowel milled keyhole) is located on the top panel, marked with a ”T”. By determing the length of the fastener in RD&T, an offset is created, moving the contact point this distance in the direction perpendicular to the surface on which the fastener located. The offset in this case was chosen to be the distance that IKEA has specified as the distance in perpendicular direction from the surface to the first stress area of the milled keyhole. This offset was applied using the length option ”d1” of the RD&T fastener options tab and is shown as ”d1”, in Figure 4.10. In RD&T, the dimensions ”A1” and ”A2” are defined as the contact diameters of the fastener (wedge dowel grooved pin) and its counterpart (wedge dowel milled keyhole) respectively at the position of the contact point. The values for these parameters was chosen according to the measures defined by IKEA on the product drawings. The contact diameters are shown as measures ”D1” and ”D2” in Figure 4.10 to prevent these dimensions from being confused with the locator points ”A1” and ”A2”.

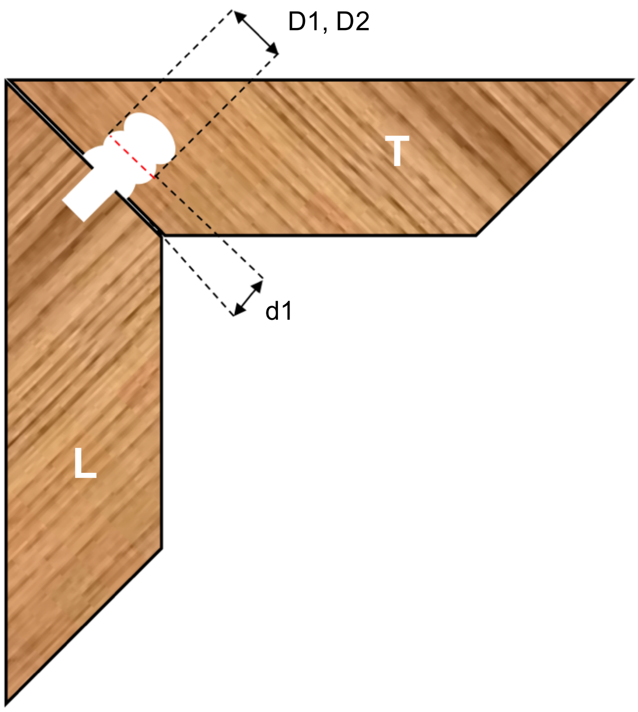


***Figure 4.10** – Contact point location and contact diameter adjustments of fastener*

4.2.4 SOLIDWORKS TOLANALYST SIMULATION

To be able to understand the current way of working at IoS and benchmark this method against the alternative of using RD&T, the project team had to study SolidWorks and learn how to use the software and its functions and tools including DimXpert and TolAnalyst. To create fair conditions for a benchmark between the ways of working using the two softwares, the same assembly was put together in both softwares. To the extent possible, the setup of measures and tolerances were defined similar in both cases. The project team learned how to use SolidWorks and its functions and tools by studying tutorials online. The theory learned was then applied on the valje frame for analysis.

The four frame panels of Valje were first individually dimensioned and toleranced acording to the IKEA product drawings using DimXpert. These parts were then assembled using the SolidWorks software tools for assembly. Interfaces were created by connecting the 45 degree surfaces and aligning the axes for the holes representing the corresponding positions for the holes of the wedge dowel grooved pins and milled keyholes. Following this, using TolAnalyst, 14 measures were defined for the frame. These are presented in Figure 4.11 and Table 4.1.

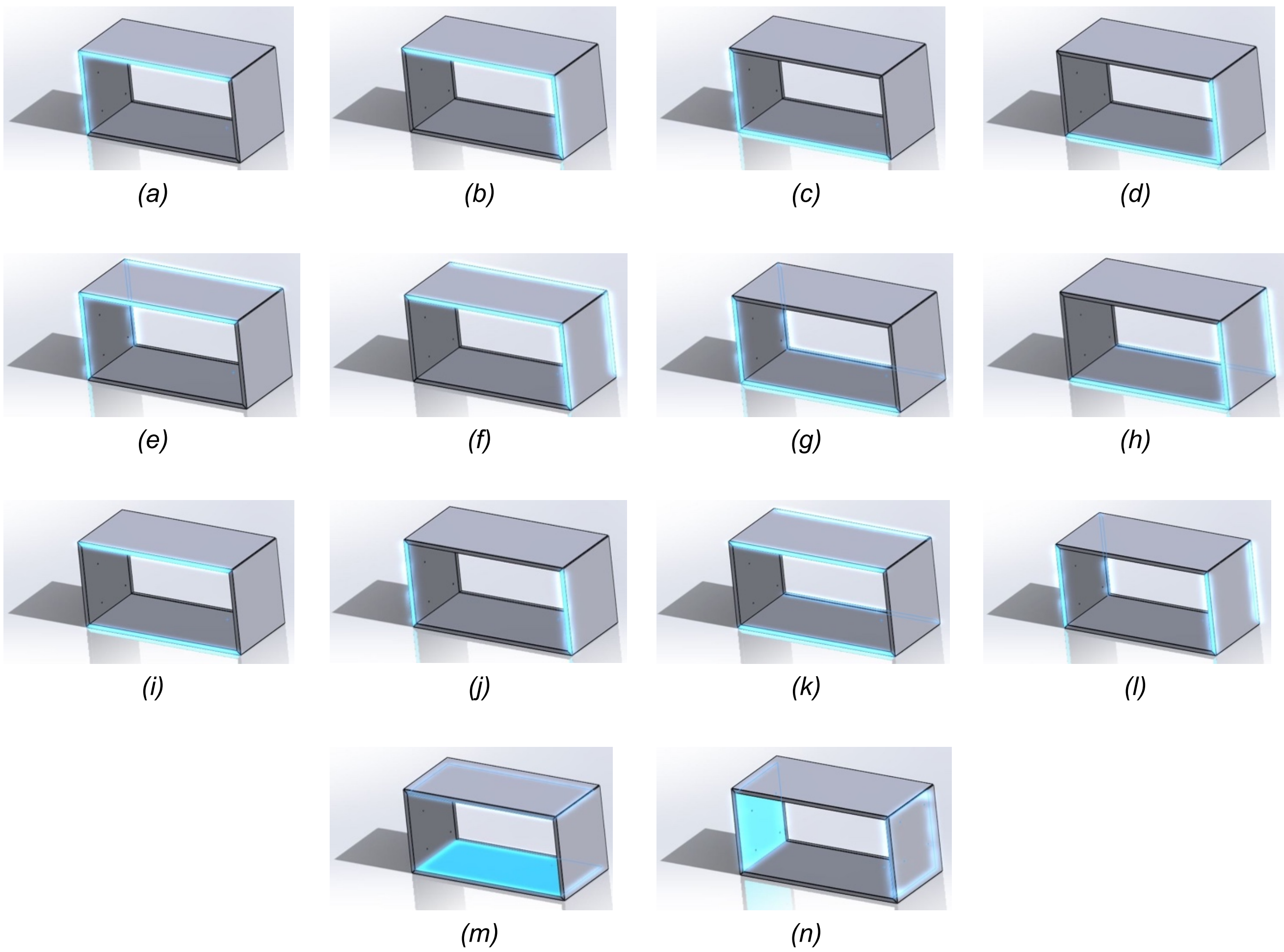


***Figure 4.11** - Measures defined using SolidWorks TolAnalyst*

Table 4.1 – *Definition of measures defined using SolidWorks TolAnalyst.*

	Measure	Definition
(a)	**Flush corner 01**	The distance in the direction normal to the common plane between the top and left side panels, on the front side of the frame.
(b)	**Flush corner 02**	The distance in the direction normal to the common plane between the top and right side panels, on the front side of the frame.
(c)	**Flush corner 03**	The distance in the direction normal to the common plane between the bottom and left side panels, on the front side of the frame.
(d)	**Flush corner 04**	The distance in the direction normal to the common plane between the bottom and right side panels, on the front side of the frame.
(e)	**Flush corner 05**	The distance in the direction normal to the common plane between the top and left side panels, on the back side of the frame.
(f)	**Flush corner 06**	The distance in the direction normal to the common plane between the top and right side panels, on the back side of the frame.
(g)	**Flush corner 07**	The distance in the direction normal to the common plane between the bottom and left side panels, on the back side of the frame.
(h)	**Flush corner 08**	The distance in the direction normal to the common plane between the bottom and right side panels, on the back side of the frame.
(i)	**Flush height front**	The distance in the direction normal to the common plane between the top and bottom panels, on the front side of the frame.
(j)	**Flush width front**	The distance in the direction normal to the common plane between the left and right side panels, on the front side of the frame.
(k)	**Flush height back**	The distance in the direction normal to the common plane between the top and bottom panels, on the back side of the frame.
(l)	**Flush width back**	The distance in the direction normal to the common plane between the left and right side panels, on the back side of the frame.
(m)	**Inner height**	The distance in perpendicular direnction between the top and bottom panels, inside the frame.
(n)	**Inner width**	The distance in perpendicular direnction between the left and right side panels, inside the frame.

For each of these measures, the assembly sequence was chosen as defined in the IKEA assembly instructions for Valje. This gives that the panels were chosen to be assembled in the order that follows;

1. (*Positioning of the left side panel*)
2. Bottom panel assembled onto the left side panel
3. Top panel assembled onto the left side panel
4. Right side panel assembled onto the top and bottom panels

The left side panel was chosen to be the ground part of the assembly and because of this the positioning of this panel was chosen as the first step of the assembly sequence. For step 2-4 of the assembly sequence, constraints were added, specifying in which order surfaces and axes were to contact and align, corresponding with the assembly sequence of Valje. This was of importance because of the assembly order contributing to variation.

For assembly sequence step 2, as shown in Figure 4.12a, the planes defined by the 45 degree angled surfaces between the bottom and left side panels were chosen as the first to contact. Following this the axes of the holes located on the same planes, representing the positions of the wedge dowel grooved pins and milled keyholes, were chosen to align. This procedure was believed to be a correct way of representing the wedge dowel grooved pin first being placed in the milled keyhole and then slided into locked position.

For assembly sequence step 3, the procedure was defined as for step 2 but for top and left side panels instead.

For the final step, assembly sequence step 4, an extra constraint step was defined. As shown in Figure 4.12b, the planes representing the 45 degree angled surfaces between the bottom and right side panels was chosen as the first to contact. Following this the corresponding planes between the top and right side panels was chosen to contact. Finally the axes of the holes located on these planes were chosen to align.

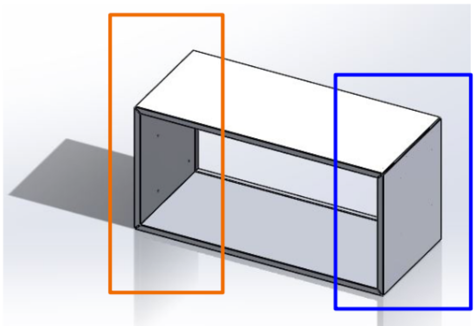


Figure 4.12 *- Assembly sequence areas*

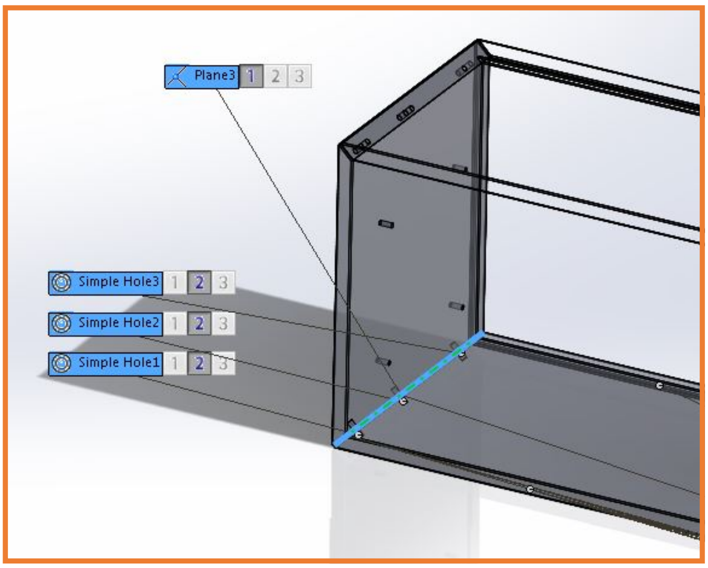


Figure 4.12a *– Constraints for assembly sequence steps 2 and 3*

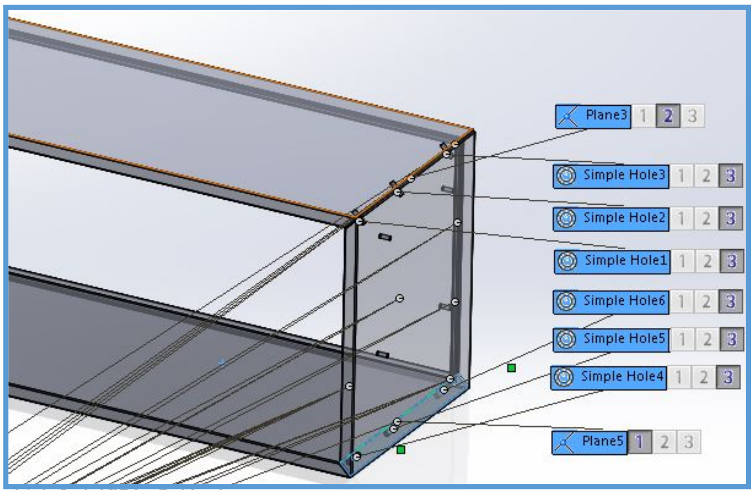


Figure 4.12b *– Constraints for assembly sequence step 4*

5 RESULTS AND DISCUSSION

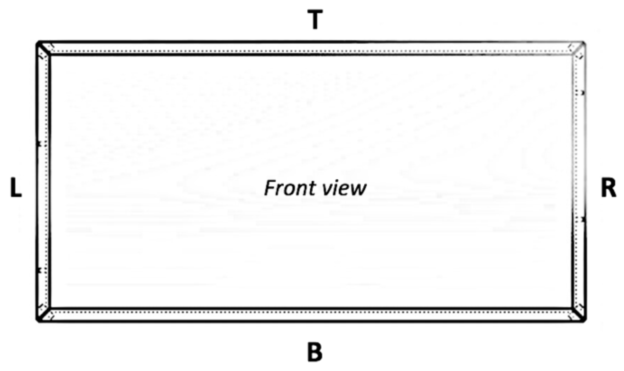
In this chapter the results of the simulations done in SolidWorks and RD&T will be presented. Following this, the results and the overall impressions of the master thesis project will be discussed. The results are presented using acronyms according to Table 5.1, describing the tolerance type and placement. Graphical representations of these acronyms are shown in Figures 5.1, 5.2 and 5.3.

Table 5.1 *- Tolerance acronyms and descriptions*

Acronym	Description
H1-L-T-*	Hole 1 on left side panel, positioned against top panel*
H2-L-T-*	Hole 2 on left side panel, positioned against top panel*
H3-L-T-*	Hole 3 on left side panel, positioned against top panel*
H1-L-B-*	Hole 1 on left side panel, positioned against bottom panel*
H2-L-B-*	Hole 2 on left side panel, positioned against bottom panel*
H3-L-B-*	Hole 3 on left side panel, positioned against bottom panel*
H1-R-T-*	Hole 1 on right side panel, positioned against top panel*
H2-R-T-*	Hole 2 on right side panel, positioned against top panel*
H3-R-T-*	Hole 3 on right side panel, positioned against top panel*
H1-R-B-*	Hole 1 on right side panel, positioned against bottom panel*
H2-R-B-*	Hole 2 on right side panel, positioned against bottom panel*
H3-R-B-*	Hole 3 on right side panel, positioned against bottom panel*
H1-T-L-*	Hole 1 on top panel, positioned against left side panel*
H2-T-L-*	Hole 2 on top panel, positioned against left side panel*
H3-T-L-*	Hole 3 on top panel, positioned against left side panel*
H1-T-R-*	Hole 1 on top panel, positioned against right side panel*
H2-T-R-*	Hole 2 on top panel, positioned against right side panel*
H3-T-R-*	Hole 3 on top panel, positioned against right side panel*
H1-B-L-*	Hole 1 on bottom panel, positioned against left side panel*
H2-B-L-*	Hole 2 on bottom panel, positioned against left side panel*
H3-B-L-*	Hole 3 on bottom panel, positioned against left side panel*
H1-B-R-*	Hole 1 on bottom panel, positioned against right side panel*
H2-B-R-*	Hole 2 on bottom panel, positioned against right side panel*
H3-B-R-*	Hole 3 on bottom panel, positioned against right side panel*
W-L	Width of left side panel
W-R	Width of right side panel
W-T	Width of top panel
W-B	Width of bottom panel
L-L	Length of left side panel, with respect to the 45 degree angle surfaces
L-R	Length of right side panel, with respect to the 45 degree angle surfaces
L-T	Length of top panel, with respect to the 45 degree angle surfaces
L-B	Length of bottom panel, with respect to the 45 degree angle surfaces
T-L	Thickness of left side panel
T-R	Thickness of right side panel
T-T	Thickness of top panel
T-B	Thickness of bottom panel

** For the RD&T results an additional letter (x,y or z) is added in the end of these acronyms, defining local direction of the tolerance.*

Figure 5.1 shows the placement of the Valje frame panels while assembled. Here the assembled frame is seen from the front.



L=Left side panel, R=Right side panel, T=Top panel, B=Bottom panel

Figure 5.1 *- Valje frame panels acronyms*

Figure 5.2 shows the placement of the holes for the Valje frame panels while assembled. The width direction for the panels are also pointed out. The front of the frame is pointed out with the notation "Front view".

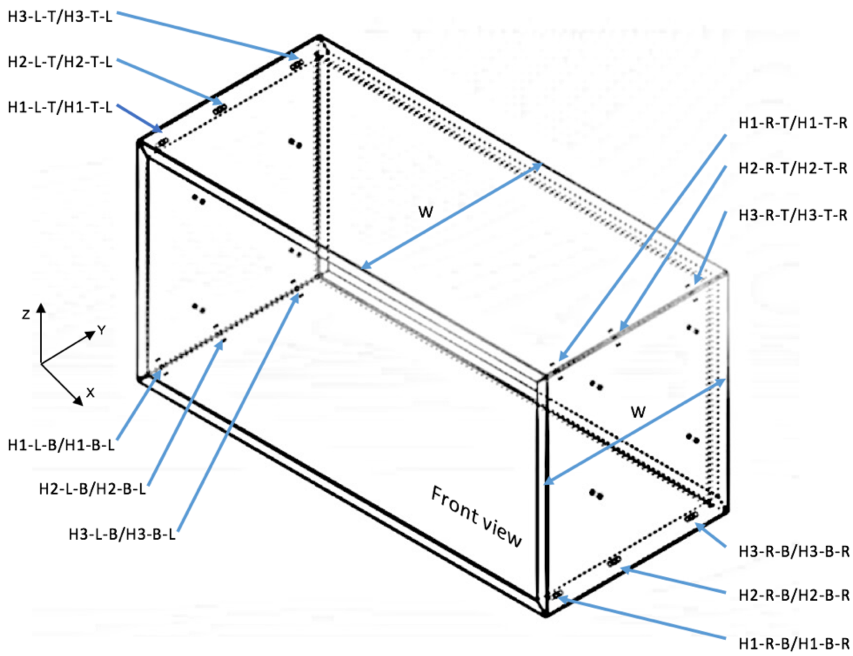


Figure 5.2 *- Valje frame tolerance acronyms placements*

Figure 5.3 points out the directions of the length tolerances for the panels, with respect to the 45 degree surfaces, while the frame is assembled. The thickness tolerances for the panels are also pointed out. Note that ”L” and ”T” only marks that length or thickness are considered but not for which panel. The following letter of the acronym determines which panel is being considered (e.g. L-L, L-T, T-L and T-T). Here the assembled frame is seen from the front.

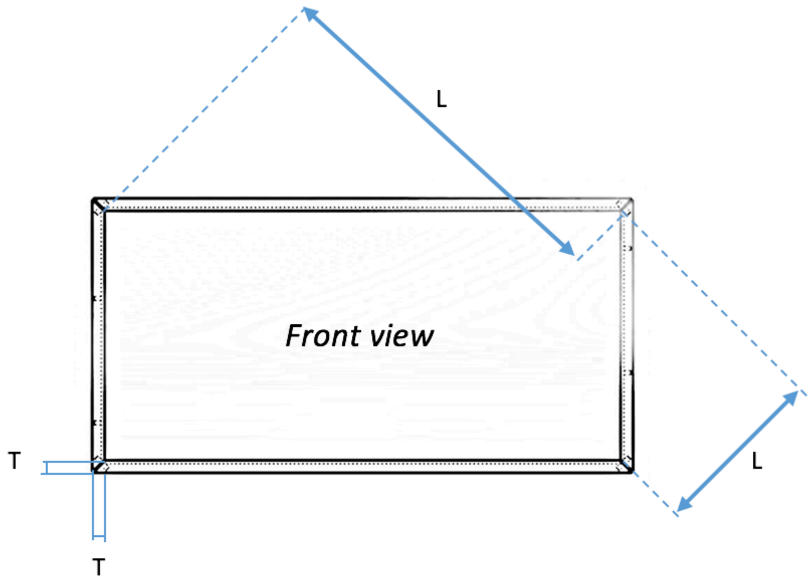


Figure 5.3 - *Valje frame tolerance acronyms placements*

5.1 MANUAL ASSEMBLY

The results of the manual assembly were perceived to be good. Aside from a crack in the back panel caused by bending stress when assembling, the flushes, gaps and other dimensional measures were of visually good result and the assembly was perceived as robust. It is not sure to say why the backpanel was too long, but it is believed to be because of some bigger failure in cutting rather than wrong set cutting tolerances.

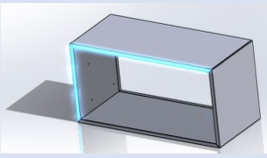
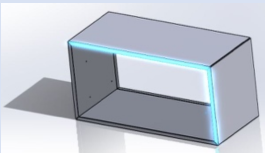
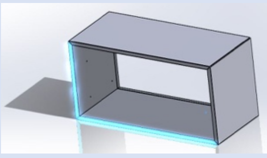
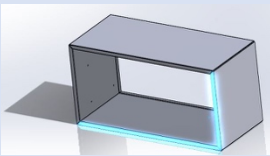
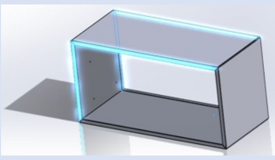
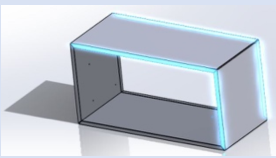
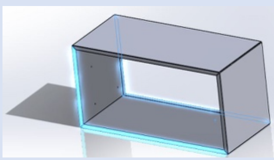
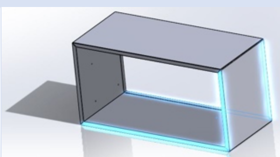
5.2 SOLIDWORKS - RESULTS

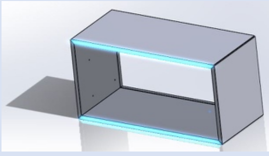
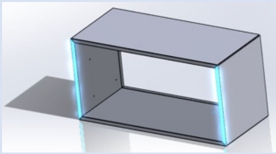
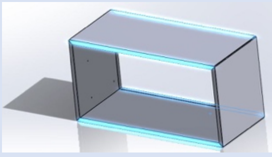
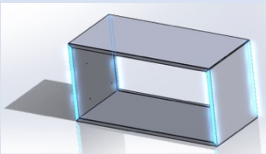
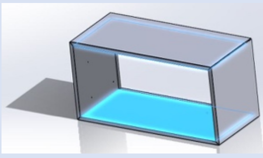
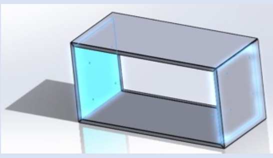
Here the results of variation analysis and contribution analysis using SolidWorks TolAnalyst will be presented.

5.2.1 VARIATION ANALYSIS

The results of the variation analysis, listed in Table 5.2, can be percieved to be quite good. However, here it can be seen that SolidWorks TolAnalyst stacks up in 1D at a time during simulation. E.g the values of ”Flush corner 02” and ”Flush corner 04” giving the same results shows that SolidWorks TolAnalyst does not consider rotations in the model. The same kind of behavior can be seen between other measures such as e.g. ”Flush height front” and ”Flush width front” as well.

Table 5.2 *- TolAnalyst variation results of the defined measures*

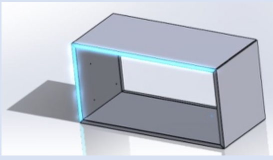
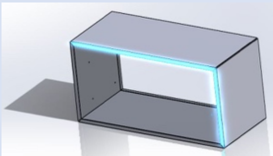
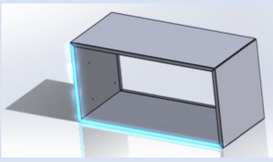
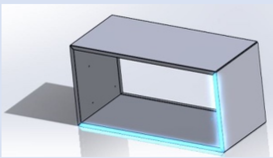
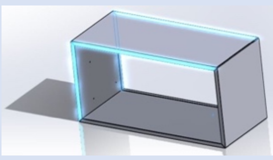
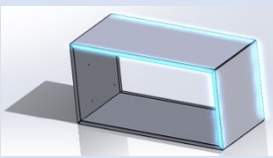
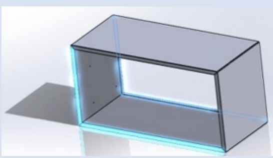
		Measure \ Value	**Nominal**	**Min**	**Max**	**RSS Min**	**RSS Max**
(a)		***Flush corner 01***	0	-0.7	0.433	-0.376	0.109
(b)		***Flush corner 02***	0	-1.233	0.967	-0.394	0.127
(c)		***Flush corner 03***	0	-0.667	0.4	-0.368	0.102
(d)		***Flush corner 04***	0	-1.233	0.967	-0.394	0.127
(e)		***Flush corner 05***	0	-1	0.6	-0.521	0.196
(f)		***Flush corner 06***	0	-1.433	1.267	-0.465	0.234
(g)		***Flush corner 07***	0	-1.067	0.6	-0.557	0.165
(h)		***Flush corner 08***	0	-1.433	1.267	-0.465	0.234

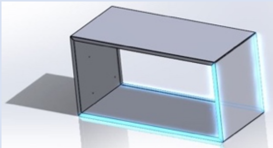
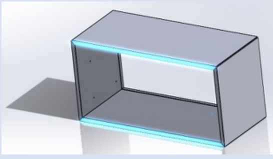
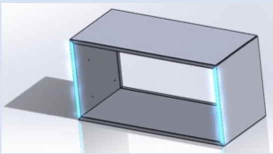
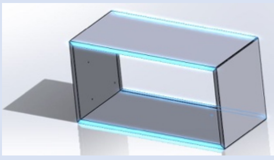
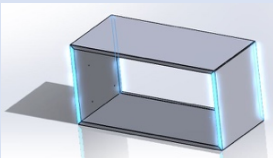
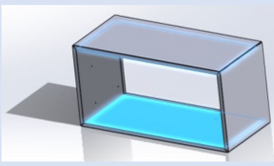
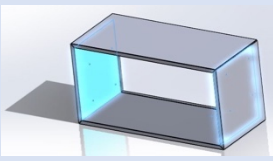
(i)		***Flush height front***	0	-1.1	1.1	-0.338	0.338
(j)		***Flush width front***	0	-1.1	1.1	-0.276	0.276
(k)		***Flush height back***	0	-1.3	1.5	-0.418	0.524
(l)		***Flush width back***	0	-1.3	1.4	-0.331	0.367
(m)		***Inner height***	312	310.91	313.09	311.689	312.311
(n)		***Inner width***	645	643.868	646.131	644.707	645.293

5.2.2 CONTRIBUTION ANALYSIS

The contribution analysis results of the simulation in SolidWorks is listed in Table 5.3. Here the 4 tolerances that gives highest amount of contribution to the variation of a measure are presented. For most of the measures, the highest contributors are the tolerances for the holes representing the position of the wedge dowels closest to the front of each frame corner. These are reasonable results since these wedge dowels are defined as the guiding pairs which the second and third wedge dowels of each frame corner follows (as described in chapter 3.3).

Table 5.3 *- TolAnalyst highest contribution results of the defined measures*

		Measure	Tolerance	Contribution (%)
(a)		**Flush corner 01**	H1-T-L	26.09
			H1-L-T	26.09
			W-L	13.04
			W-T	13.04
(b)		**Flush corner 02**	H1-T-R	6.67
			H1-R-T	6.67
			W-R	6.67
			W-T	6.67
(c)		**Flush corner 03**	H1-L-B	27.27
			H1-B-L	27.27
			W-L	13.64
			W-B	13.64
(d)		**Flush corner 04**	H1-R-B	6.67
			H1-B-R	6.67
			W-R	6.67
			W-B	6.67
(e)		**Flush corner 05**	H1-L-T	22.22
			H1-T-L	22.22
			W-T	22.22
			W-L	11.11
(f)		**Flush corner 06**	W-T	12.50
			H1-R-T	12.50
			H1-T-R	6.25
			W-R	6.25
(g)		**Flush corner 07**	W-B	21.43
			H1-L-B	21.43
			H1-B-L	21.43
			W-L	10.71

(h)		***Flush corner 08***	W-B	12.50
			H1-R-T	12.50
			H1-R-B	6.25
			W-R	6.25
(i)		***Flush height front***	H1-T-L	13.33
			H1-L-T	13.33
			H1-L-B	13.33
			H1-B-L	13.33
(j)		***Flush width front***	H1-B-L	7.69
			H1-L-T	7.69
			H1-R-B	7.69
			H1-T-L	7.69
(k)		***Flush height back***	H1-T-L	23.53
			H1-B-L	11.76
			W-B	11.76
			H1-L-T	11.76
(l)		***Flush width back***	H1-R-T	12.50
			W-L	12.50
			H1-T-R	6.25
			H1-L-B	6.25
(m)		***Inner height***	L-L	16.28
			W-T	8.70
			W-B	8.70
			H3-L-T	8.54
(n)		***Inner width***	L-R	10.62
			L-T	10.62
			W-H	7.51
			H3-L-R	7.37

5.3 SOLIDWORKS - DISCUSSION

The results of Tables 5.2 and 5.3 show that for a number of defined measures, e.g. the flushes in corners 02 *(b)* and 04 *(d),* the amount of variation is equal and there is a number of tolerances listed as highest contributors that contribute equally. Aside from the listed tolerances in these cases, there are also additional tolerances that give equal contribution for these measures. A reason for these results is the fact that SolidWorks calculates in 1D at a time during analysis. For measures where the tolerances are defined as being of the same type and range and the included parts are defined to have the same assembly sequence and assembly constraints, the variation results will be equal when tolerance stack-up is performed in 1D at a time.

5.4 RD&T

Here the results of the types of analyzes performed with RD&T rigid and non-rigid simulations will be presented.

5.4.1 RD&T - RIGID SIMULATION – RESULTS

In this section the results of the RD&T rigid simulation will be presented. This includes the results of the stability analysis, variation analysis and contribution analysis.

5.4.1.1 STABILITY ANALYSIS

Stability analysis is a method that aims to evaluate the robustness of a design and the geometrical degree of coupling of an assembly. The values of the matrix elements of the stability matrix show how each part is affected by other parts. If the value is bigger than 1, it means that the input variation will be suppressed by the design concept. (Wärmefjord, K., 2004) Figure 5.4 shows the stability matrix for the frame assembly of Valje. On the bottom row, the robustness of the right side panel is shown. It is shown that the positioning scheme of right side panel positioned against the bottom panel affects the most, followed by the right side panel positioned against itself.

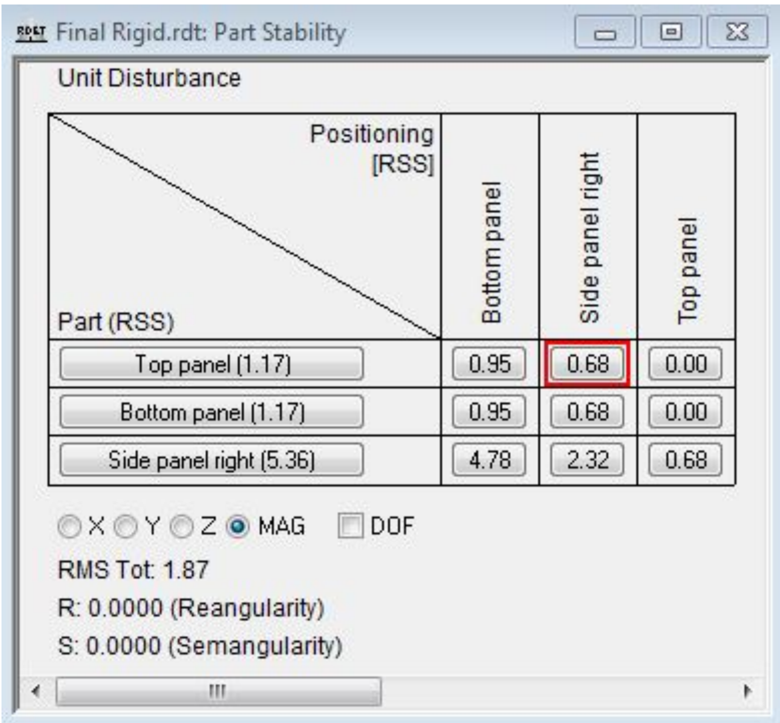


Figure 5.4 *– Stability matrix results of RD&T rigid simulation*

The color coded stability analysis result of the rigid Valje frame assembly is shown in Figure 5.5. The function of color coding is quick, direct and easy to understand. Here the scale runs from blue to red where blue represents low sensitivity to variation and red represents high sensitivity to variation. Based on the results shown in Figure 5.5 it can be seen that the right side panel is more sensitive to variation.

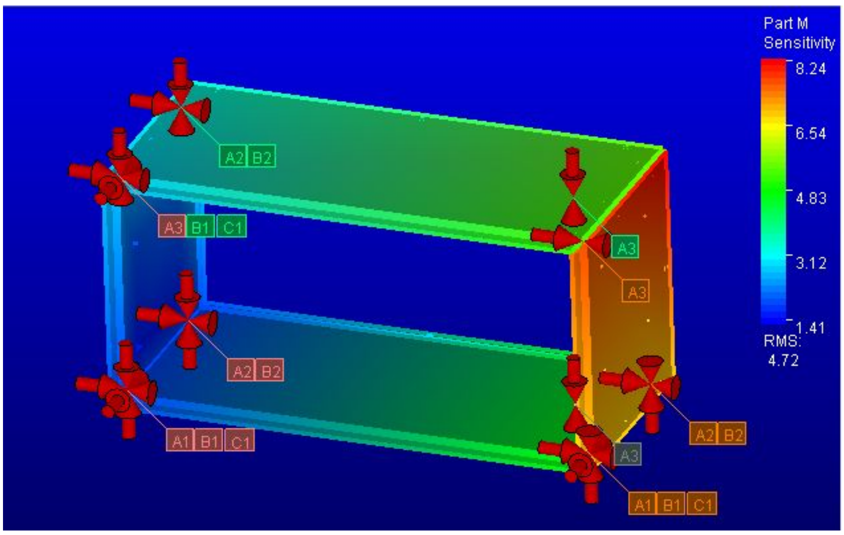


Figure 5.5 *– Stability analysis of RD&T rigid simulation*

5.4.1.2 VARIATION ANALYSIS

The results of RD&T rigid variation analysis for the defined RD&T measures (see Table 4.1), is listed in Table 5.4. The results are based on variation analysis of 1000 itterations, representing 1000 assembled frames. The results show that the variation is higher for the measures ”Flush corner 02”, ”Flush Corner 06”, ”Flush Height 02” and ”Flush Height 04”. Since the corners 02 and 06 are defined in the upper right corner, front and back seen from the front view, it is reasonable that these measures are exposed to higher amount of variation. This because these corners, as seen in Figure 5.5, are not as well defined as the other corners in terms of locating scheme. This is due to the fact that a rigid model in RD&T can not be overconstrained. The ”Flush height 02” and ”Flush height 04” measures are defined between top and bottom panels close to these corners which makes the results of high amount of variation reasonable here as well. The same kind of behavior can also be seen in ”Flush Width 01” and ”Flush Width 03” as well since these measures are defined close to these corners as well.

***Table 5.4** – RD&T variation results of defined measures for rigid simulation*

Measure \ Value	**Nominal**	**Range**	**6 sigma**	**Mean**
Flush Corner 01	0	0.571	0.556	-0.000851
Flush Corner 02	0	2.98	2.58	-0.00121
Flush Corner 03	0	0.621	0.577	-0.00552
Flush Corner 04	0	0.579	0.573	0.00438
Flush Corner 05	0	0.578	0.563	0.00196
Flush Corner 06	0	2.94	2.56	-0.00218
Flush Corner 07	0	0.578	0.556	-0.00248
Flush Corner 08	0	0.526	0.573	0.00299
Flush Height 01	0	0.957	0.883	-0.00428
Flush Height 02	0	2.39	2.16	-0.00348
Flush Height 03	0	0.938	0.882	-0.00444
Flush Height 04	0	2.31	2.17	-0.00246
Flush Width 01	0	1.92	1.74	-8.44e-005
Flush Width 02	0	1.23	1.2	-0.00711
Flush Width 03	0	1.83	1.72	-0.000383
Flush Width 04	0	1.17	1.2	-0.00365
Inner Height 01	312	0.6	0.578	312

Inner Height 02	312	0.631	0.534	312
Inner Height 03	312	0.67	0.615	312
Inner Height 04	312	0.902	0.93	312
Inner Width 01	645	0.614	0.523	645
Inner Width 02	645	0.633	0.561	645
Inner Width 03	645	1.04	0.879	645
Inner Width 04	645	0.617	0.61	645

5.4.1.3 CONTRIBUTION ANALYSIS

Due to the high number of measures and dimensions defined for the RD&T simulations, all the RD&T rigid contribution analysis results will not be presented here, since this would mean including an extra hundreds of pages. Instead the contribution results of measures near two corners will be presented. The two corners chosen for this is corner 01 and corner 06. These were chosen because the variation results in Table 5.4 shows that the measures defined near corner 06 results in high amount of variation and the measures defined near corner 01 results in more regular amount of variation in comparison. Because of this, the values for contribution for the measures near each of these corners will be presented and compared.

Table 5.5a shows the contributions results of the defined measures near corner 01. It lists the amounts of contribution for the highest contributing tolerances for each measure. Table 5.5b does the same thing but for the defined measures near corner 06.

Table 5.5a *– RD&T contribution results for rigid simulation near corner 01*

Measure	Tolerance	Percentage (%)
Flush Corner 01	H1-L-T-X	27.6
	H1-T-L-X	27.6
	W-T	13.8
	W-L	13.8
Flush Height 01	H3-L-B-Y	11.8
	H1-L-B-Y	11.8
	H1-L-B-X	11.0
	H1-B-L-X	11.0
	H1-T-L-X	11.0
	H1-L-T-X	11.0
Flush Width 01	H3-B-L-Y	28.1
	H1-B-L-Y	28.1
	H1-B-L-X	3.1
	H1-L-B-X	3.1

Inner Height 01	H1-B-L-Y	16.3
	H1-L-T-Y	16.3
	H1-T-L-Y	16.3
	H1-L-B-Y	16.3
	T-B	6.6
	T-T	6.6
Inner Width 01	H1-R-T-Y	14.8
	H1-T-R-Y	14.8
	H1-L-T-Y	14.8
	H1-T-L-Y	14.8
	T-L	7.9
	T-R	7.9

Table 5.5b *– RD&T contribution results for rigid simulation near corner 06.*

Measure	***Tolerance***	***Percentage (%)***
Flush Corner 06	H1-L-B-Y	12.9
	H3-L-B-Y	12.9
	H3-B-L-Y	12.7
	H1-B-L-Y	12.7
Flush Height 04	H1-L-B-Y	17.1
	H3-L-B-Y	17.1
	H1-L-T-Y	7.7
	H3-T-L-Y	7.7
	H3-L-T-Y	7.7
	H1-T-L-Y	7.7
Flush Width 03	H3-B-L-Y	28.1
	H1-B-L-Y	28.1
	H1-B-L-X	3.1
	H1-L-B-X	3.1
Inner Height 04	H3-B-L-Y	7.8
	H3-T-L-Y	7.7
	H3-L-T-Y	7.7
	H3-L-B-Y	7.7
	H1-T-L-Y	7.4
	H1-L-T-Y	7.4
Inner Width 03	H3-L-B-Y	7.9
	H3-B-L-Y	7.9
	H3-R-B-Y	7.9
	H3-B-R-Y	7.9
	H1-L-B-Y	7.5
	H1-B-L-Y	7.5

5.4.2 RD&T - RIGID SIMULATION – DISCUSSION

In RD&T rigid simulation, the model contains dependent tolerances, thus no stability simulation is performed for the real tolerances. The 12 fasteners representing the wedge dowels in RD&T non-rigid simulation can not be used for rigid simulation since the parts can not be bent or overconstrained in this type of simulation. This means that if fasteners would have been used, some of them would have had to be neglected for the simulation to work. Because of the product not being allowed to be overconstrained, the result will be unfair in some areas because of these not being defined equally using locating shemes (as discussed in chapter 5.4.1.2). This can be seen comparing Tables 5.5a and 5.5b where corner 01 is better defined with locating schemes than corner 06. The results of Table 5.5a shows more accourate results of contribution while Table 5.5b shows more equally distributed contributions between the dimensions for corner o6 since this corner is not as well defined as corner 01.

When discussing with IoS representatives, it was explained that as of now, IoS does not have any set requirements on overall shape of Valje. This means that no requrements on gaps, flushes and other measure have been stated. This makes it hard to evaluate which of the measures that are out of control because just using range, mean value and 6 Sigma value is quite subjective. It would be more objective to set requirements or specifications on certain measures since the values of capability indices C_p and C_{pk} can be used for analyzing the variation of an assembly.

The contribution analysis results show that the wedge dowel grooved pin position tolerance and the milled keyhole position tolerance are the tolerances that give most contribution to variation, especially the front wedge dowel of each corner. In some cases the panel thickness and width tolerances give a little bit of contribution to variation, but not as much. It can be seen that other tolerances, such as tolerances for surface profile and angularity of the wedge dowel grooved pin and milled keyhole, do not contribute much to variation in this case.

5.4.3 RD&T - NON-RIGID SIMULATION – RESULTS

Here the results of the RD&T non-rigid simulation will be presented. This includes the results of the stability analysis, variation analysis, contribution analysis and stress analysis.

5.4.3.1 STABILITY ANALYSIS

The color coded stability analysis result of the non-rigid Valje frame assembly is shown in Figure 5.6. Here it can be seen that there is a higher risk of variation in the two upper corners (corner 01 and 02).

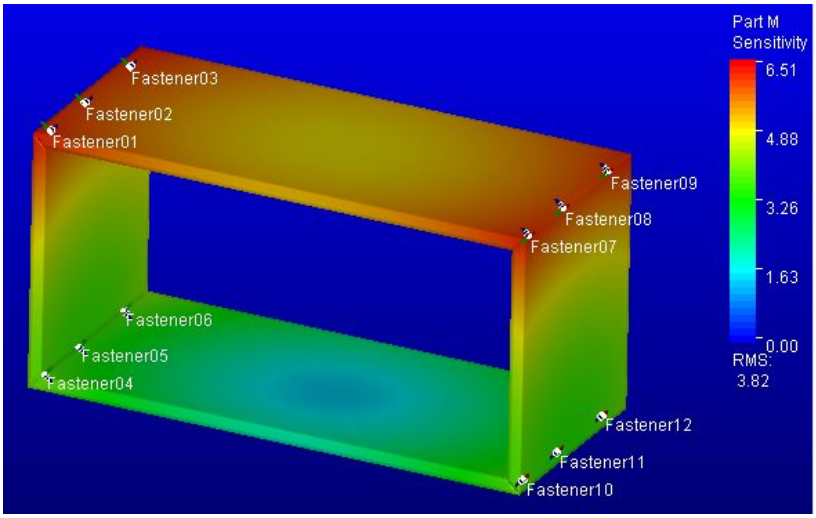


***Figure 5.6** – Stability analysis of RD&T non-rigid simulation*

5.4.3.2 VARIATION ANALYSIS

The results of RD&T non-rigid variation analysis for the defined RD&T measures (see Table 4.1), is listed in Table 5.6. The results show that the all the measures of a specific measure category (”Flush corner”, ”Flush height”, ”Flush width”, ”Inner height” and ”Inner width”) have quite equal values. This is due to the fact that the non-rigid RD&T model can be overconstrained and thus the 12 fasteners could be utilized. By positioning the fasteners equally in each corner the variation is distributed more evenly over the product. This gives more realistic results compared to the results of rigid simulation.

***Table 5.6** – RD&T variation results of defined measures for non-rigid simulation*

Measure \ Value	**Nominal**	**Range**	**6 sigma**	**Mean**
Flush corner 01	0	0.566	0.562	-0.061
Flush corner 02	0	0.585	0.572	-0.179
Flush corner 03	0	0.535	0.563	0.12
Flush corner 04	0	0.57	0.543	0.12
Flush corner 05	0	0.62	0.569	-0.151
Flush corner 06	0	0.622	0.571	-0.124
Flush corner 07	0	0.611	0.576	0.183
Flush corner 08	0	0.675	0.572	0.17
Flush Height 01	0	1.17	1.12	0.00368
Flush Height 02	0	1.11	0.811	-0.0596

Flush Height 03	0	1.20	1.11	-0.023
Flush Height 04	0	1.08	0.86	0.0207
Flush Width 01	0	1.53	1.43	-0.1
Flush Width 02	0	0.753	0.742	-0.0466
Flush Width 03	0	1.56	1.4	-0.024
Flush Width 04	0	0.737	0.759	0.00618
Inner Height 01	312	0.755	0.64	312
Inner Height 02	312	0.621	0.603	312
Inner Height 03	312	0.726	0.694	312
Inner Height 04	312	0.731	0.649	312
Inner width 01	645	0.586	0.54	645
Inner width 02	645	0.697	0.547	645
Inner width 03	645	0.558	0.586	645
Inner width 04	645	0.669	0.597	645

5.4.3.3 CONTRIBUTION ANALYSIS

The results of the non-rigid contribution analysis show quite equal distribution of the values within the same measure categories (”Flush corner”, ”Flush height”, ”Flush width”, ”Inner height” and ”Inner width”). Because of this only the results of one measure of each category are presented in Table 5.7.

Table 5.7 *– RD&T contribution results of defined measures for non-rigid simulation*

	Tolerance	**Percentage (%)**
Flush Corner 01	H1-L-T-X	27.0
	H1-T-L-X	27.0
	W-T	13.5
	W-L	13.5
Flush Height 01	H3-B-R-Y	13.1
	H3-R-B-Y	13.1
	H1-B-R-Y	9.4
	H1-R-B-Y	9.4
	H3-R-T-Y	4.1
	H3-T-R-Y	4.1
Flush Width 01	H3-B-R-Y	9.1
	H3-R-B-Y	9.1
	H3-R-T-Y	9.0
	H3-T-R-Y	9.0

	H1-R-T-Y	7.0
	H1-T-R-Y	7.0
Inner Height 01	H1-B-R-Y	15.4
	H1-R-B-Y	15.4
	H1-R-T-Y	14.1
	H1-T-R-Y	14.1
	T-T	5.6
	T-B	5.6
Inner Width 01	H1-L-T-Y	17.2
	H1-T-L-Y	17.2
	H1-R-T-Y	9.3
	H1-T-R-Y	9.3
	T-R	7.2
	T-L	7.2

5.4.3.4 STRESS ANALYSIS

The stress condition is highly dependant on the load, boundary conditions and material. In this case no external forces or loads were applied to the model, the loads are generated by the tolerances. For instance an offset tolerance in local z-direction of a fastener resemble a compressing force, pulling the two mating parts together. Another example is that if the distance tolerance for two wedge dowel grooved pin holes is smaller than for two milled keyholes, the result will be additional stress in the wedge dowel assembly. Because no external forces or loads were added, the results were local stresses in the fastener areas as seen in Figure 5.7.

The boundary conditions of the non-rigid Valje frame model includes each panel locked in 6 DOF by 6 wedge dowels, 12 wedge dovels in total for all 4 frame panels. The material is simplified by assuming it as being made out of isotropic particle board. Table 5.8 shows the stress results for each fastener area, generated by running a simulation of 1000 iterations. stress value. It can be seen that there is a decreasing mean stress value, from front to back, for the three fasteners of each corner. This is reasonable results given that the front wedge dowel of each corner is the guiding wedge dowe grooved pin and milled keyhole pair that the other two wedge dowels follows. These results are values that can be used for further research by IoS. Since there are no additional loads and forces applied in RD&T and the material structural data is not complete for this thesis, it could be considered as further work to use a FEA software to further analyze these values.

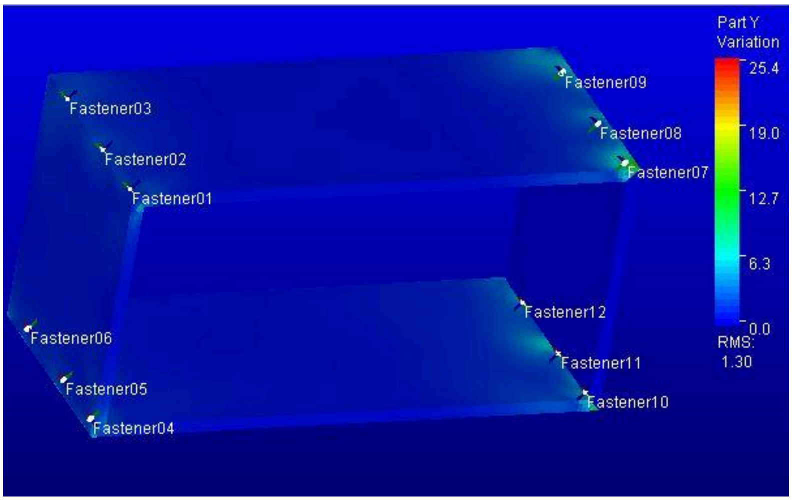


***Figure 5.7** – Stress analysis results*

***Table 5.8** – RD&T contribution results of defined measures for non-rigid simulation*

	Range (MPa, N/mm^2)	**Mean** (MPa, N/mm^2)	**Max** (MPa, N/mm^2)
Fastener 01	4.51	3.13	5.42
Fastener 02	5.31	2.36	5.66
Fastener 03	4.06	1.30	4.17
Fastener 04	4.19	3.26	5.42
Fastener 05	4.91	2.37	5.38
Fastener 06	3.97	1.48	4.1
Fastener 07	5.23	3.50	6.6
Fastener 08	5.59	2.67	6.24
Fastener 09	3.96	2.11	4.33
Fastener 10	4.62	3.06	5.49
Fastener 11	5.59	2.37	5.83
Fastener 12	3.49	1.21	3.59

5.4.4 RD&T - NON-RIGID SIMULATION – DISCUSSION

For non-rigid simulation in RD&T, a superpart containing all four Valje frame panels was created. The superpart was created in order to make it possible to use the fasteners in the model. Using fasteners was a good way of resembling the assembly method of the outer frame of Valje. A drawback of this is however the fact that the assembly sequence is not considered here, thus the influence of variation that the assembly sequence brings to the final result can not be obtained.

Comparing variation results obtained with rigid simulation against non-rigid simulation, it can be seen that the rigid simulation can give inaccurate results in areas lacking support of locating points, while non-rigid simulation gives more even results of variation. To be able to overconstrain the assembly using the 12 fasteners, gives a better distribution of the variation over the whole product. This can be considered as better and more realistic results than the results obtained performing rigid simulation. In this specific case, the variation results of measures in areas well defined with locating schemes for rigid simulation, compared with the variation results of measures in the same areas for non-rigid simulation, shows quite similar results. Based on this it can be seen that the material is quite stiff and does not affect variation that much.

By observing the results of the non-rigid simulation contribution analysis, it is seen that the tolerances for positioning the holes for the wedge dowel grooved pin and the milled keyhole contribute with most variation in the final assembly.

5.4.4.1 RD&T NON-RIGID SURFACE MESH SIMULATION

In RD&T, surface mesh can be used to model composite material. By doing this the material can be described to better resemble the real material by defining layers and sets. This type of simulation was planned to be done for this thesis, but due to lack of material properties for all the materials of the Valje frame panels, as well as limited project time, this work was started but not fully completed. It would be interesting to further investigate the surface mesh model in the future to see the resulting variation in the model when the material is even further defined and more realistc.

5.5 ADDITIONAL DISCUSSION

Here the topics that are not connected to the results of a specific type of simulation will be discussed.

5.5.1 SOLIDWORKS OR RD&T

In this thesis three different ways of modeling have been investigated and used for analysis; rigid modeling in SolidWorks, rigid and non-rigid modeling in RD&T. The main difference between the three ways of modelling has been found to be the level of details and information that is being included in the analysis. The more information the analysis is based on the longer the calculation time, but there is a better chance of having more accurate results. The simplest way of modeling was found to be using SolidWorks and its add ons. Based on the results, SolidWorks might be the software that is perceived to be more user friendly and quick to use in terms of defining measures to quickly achieving results. However SolidWorks is lacking in areas which can affect the result badly. SolidWorks does not do Monte Carlo analysis which means that the result is not based on probability but only on stacking values that might not apply to possible situations. SolidWorks also does not consider material properties. A model analyzed in SolidWorks is a solid model, which neglects the effects that a non-rigid model might have on the results. Another major drawback with SolidWorks is that the calculation is done in 1D at a time. This might give inaccurate results because dimensions in one direction might affect dimensions in another direction. Since SolidWorks neglects this, it does not consider rotation which might give inaccurate results.

When using RD&T, the rigid and non-rigid modeling is believed to be the second best and best option for analysis. The drawbacks using RD&T can be the amount of time that it takes to define tolerances, measures, locating schemes, eventual contact points and fasteners etc. In rigid modeling there is also a drawback that the assembly sequence of the product has to be defined in a way so that the product does not get overconstrained nor caught in a dependency loop. For non-rigid modelling the material properties are considered in the analysis. This will give a more accurate result given that the correct material of the product can be considered. Since the products are allowed to be overconstrained, the support points can be adapted to increase the stability and distribute the variation more evenly over the product. However the parts have to be meshed and the number of nodes will affect the calculation time.

In both rigid and non-rigid modeling, RD&T considers simultaneous calculations in three dimensions. This gives conditions for more accurate results because of the dependency that results in one direction has effect on the results of the other directions.
Using a software as SolidWorks might work on a smaller scale, but since IoS have expressed big plans and a desire to expand their franchise in time, it would be highly recomended for them to move over to RD&T to use for tolerancing and variation simulation. The time that is being added because of increased calculation and simulation time can be regained by considering the fact that once the locating schemes of the parts and fasteners of RD&T has been defined, these can be reused and patterned later on. IoS might want to keep SolidWorks and other softwares used for modelling and finite element simulations, but it would be a good choice to implement RD&T in the process for assembly, tolerancing and for analysing variation, stability, contribution. RD&T could also be used for more basic stress analysis to see that the concept works before doing a full FEA analysis using additional software. If IoS´s vision is to expand even further and explore new engineering ways of working, the time and effort of implementing RD&T is sure to pay off with good results from non-rigid analysis.

5.5.2 MODIFICATIONS FOR FASTENER OPTIONS TAB

To make the implementation of RD&T at IoS easier, there is a number of modifications and adjustments that can be implemented in the software. These implementations would adapt the software to best suit the way of working at IoS in Älmhult. This would include implementing a number of additional settings and adjustable parameters to the fastener options tab. If doing so, IoS would be able to adjust the fastener to best fit the occation of use, before moving into production. By doing this, additional work in form of late changes during production can be prevented. Final decisicions on which adjustable parameters that would be of interest to implement could be considered as future work. However, here follows a number of changes that the project team has discussed as good implementations.

5.5.2.1 OFFSET

As of now, there is no way to add an offset to a fastener directly in the fastener options tab. Now, the user has to first position the fastener and then apply a separate offset tolerance on the same position as the fastener. This procedure results in extra work which can be time consuming, especially if the number of fasteners in the product is high. There is also a risk of mistakes caused by the human factor. Since this includes a higher number of work steps to keep track of, this might result in mistakes such as missing offsets, alternating values etc.

5.5.2.2 DEPENDENCY TOLERANCES

Because of how IoS drilling process for the panels is structured, it is necessary to add dependency tolerances on hole positions and reference points. As of now, it is not possible to add tolerances dependant with a reference point in the fastener options tab. As in the case with offsets, these must be added as separate tolerances which then are set as dependant of the reference point. This requires extra work and it is easy to make a mistake because of the human factor. It would make the work process easier if the position tolerances of holes could be set as dependant to reference points in the fastener options tab.

5.5.2.3 SHAFT LENGTH AND DIAMETER

If the user was able to specify the shaft length and diameter for the fastener, it would bring additional information to the analysis. During stress analysis the result could give a picture if the fastener itself or the material in the area where the fastener shaft is positioned is exposed to high levels of stress. This is considered to be of value for IoS since they are using various types of wedge dovel pins. For example, as mentioned in the product chapter, there are two types of wedge dowel pins used in Valje. The grooved pins used in the frame are made out of wood while the pins used in the drawers are made of plastic material. These pins have different shapes and dimensions, including length and diameter of head as well as shaft.

5.5.2.4 TEMPLATES

If IoS are going to use standard dimensioned wedge dowels for multiple future products, it could be an option to include templates with predefined dimensional values for these. For example, if adaptations were to be done on Valje, the user would just have to choose one of the two predefined types of wedge dowel pins used in the product and pick a node to position it on. This way it would save time and reduce possible errors. Of course the option of the user manually defining the parametric values should be kept as well.

6 CONCLUSION AND FURTHER WORK

6.1 CONCLUSION

Here the conclusions of the thesis will be presented. These are based on the answers of questions derived from the main goal of the thesis, which has been to compare the current way of working at IKEA using tolerance analysis software SolidWorks TolAnalyst against using RD&T.

- ***SolidWorks TolAnalyst or RD&T?***
  - Basically this is not a ”yes or no” question. When chosing a tolerance analysis software, the choice is highly dependant on the situation and the conditions. However the selection can be based on the expected outcome of the analysis. In this case it is a matter of what is more important; that the software is quicker and easier to use or if you want defined results with high accuracy.

  - SolidWorks TolAnalyst is quick to use and it is not necessary to import/export files from/to other software environments. However SolidWorks TolAnalyst has some obvious shortcomings that in some cases cause the software to give inaccurate results. E.g. the fact that SolidWorks TolAnalyst only performs 1D tolerance stack-up, which does not consider rotations in 3D. The lack of using statistical distribution and not being able including material properties are also considered as big shortcomings.

  - RD&T can be much more time expensive compared to SolidWorks TolAnalyst. It does however have the posibility give more defined and accurate results because of it using 3D tolerance stack-up and statistical distribution to predict variation.

- ***RD&T rigid or non-rigid simulation?***
  - By benchmarking the two RD&T simulation types according to the intended situation of use, suggestions on which simulation type to choose can be given.

  - Rigid simulation is relatively faster than non-rigid simulation in terms of preparing CAD-models and simulation time. But the fact that rigid simulation treats the included parts as rigid gives that material properties can not be considered, neither can the model be overconstrained. This can result in a situation where some of the assembly interfaces are not being included in the locating scheme, like a couple of the wedge dowels in the case of assembling the frame of Valje. This can result in unrealistic variation in areas which have no locator points.

- Non-rigid simulation requires top of the line computers in terms of processing power. This is necessary since FEA is embedded in the simulation to capture the displacement of the nodes and the deformation of the parts. The calculation of the compliant matrices makes this method time consuming. The results of the method is however well defined and more accurate since the parts could be overconstrained, variation could be equally distributed over areas and the included parts are not allowed to penetrate each other. Material properties are also taken into consideration in non-rigid simulation. Depending on mesh type, the materials can either be of isotropic kind (solid mesh) or complexed anisotropic kind (surface mesh).

- ***Evaluation of the tolerances set for Valje***
  - The evaluation is done based on a combination of results collected by performing rigid simulation in SolidWorks TolAnalyst and rigid and non-rigid simulation in RD&T.
  - The overall shape of Valje is considered to be quite good, but since there are no set requirements for overall shape, the evaluations are somewhat subjective.
  - By looking at the contribution results, the front wedge dowel grooved pins and milled keyholes of each corner are the tolerances that contribute the most to variation. In some cases the thickness and width tolerances give second highest contribution. It is seen that the angularity tolerance of the 45 degree surfaces as well as the surface profile tolerances for both wedge dowel grooved pins and milled keyholes give low contribution to final variation. If the overall shape variation is considered good enough, these tolerances can be loosed slightly to reduce production cost. However, if the gap and flush results are evaluated and found to be bad, the positioning tolerances of the wedge dowel grooved pins and milled keyholes should be tightened.

- ***What types of analysis are possible to conduct using RD&T?***
  - Variation analysis is one of the main functions of RD&T, used to predict the total variation of the final assembly. This gives that RD&T can be used when all the tolerances are determined or roughly set. In combination with variation analysis, a contribution analysis can be performed using RD&T to inspect which sources contribute most to variation. These results can then be compared against target values and changes can be made to the sources giving most contribution to reach the target values.

- RD&T can also be used for stability analysis in the early design phase to make the design concept as robust as possible. Stability analysis determines the design sensitivity due to position of locators. It can quickly indicate and point out critical areas by color coding the analyzed geometry. The more robust a design concept is, the lower is the sensisitivity to variation.

- ***How to use RD&T?***

  The general procedure of using RD&T;

  - ***Import geometries***
    It is possible to model geometries in RD&T, but normally it would be time consuming because of the geometries being of high complexity. Because of this it is recomended to import geometries, created in other CAD software and FEM tools, into RD&T.

  - ***Define locating scheme(s)***
    Adjusting a locating scheme is one of the main parameters of controlling variation. It defines how parts are locked in space and assembled.

  - ***Add tolerance(s)***
    Tolerances is another main parameter of variation. It determines the allowed deviation of the product. RD&T uses GD&T as standard when setting tolerances.

  - ***Add measure(s)***
    Measures are defined on points or between points, in critical or interesting areas. RD&T offers several types of measures, e.g. point self, point-to-point, positioning, line-self etc.

  - ***Analyze***
    Stability, variation and contribution analysis are the main types of analysis done in RD&T. Additional stress analysis can be performed. Stability analysis defines the robustness of an assembly concept, Monte Carlo based statistical variation simulation defines the final variation of an assembly and a contribution analysis gives a ranked list of tolerances contribution to variation.

6.2 FUTURE WORK

The main scope of this master thesis project has been to benchmark the current way of working at IoS in Älmhult, using SolidWorks DimXpert and TolAnalyst for tolerance analysis, against using the CAT-tool RD&T. This has been done by performing various kinds of analyses in the two softwares for a chosen IKEA furniture, the dresser Valje. SolidWorks has been used for variation and contribution analysis of a rigid model, while RD&T has been used for variation, stability, and contribution analysis of rigid and non-rigid models as well as stress analysis of a non-rigid model. For non-rigid simulation in RD&T, preparations have been done for analysis with solid meshes as well as surface meshes. The analysis of the surface mesh was not fully finished due to limited informtion of material data and lack of project time. The non-rigid surface mesh model can be object for further investigation in the future. When further developed, the results gathered from non-rigid simulation using this type of mesh can be compared against the results of non-rigid simulation of the solid mesh model. Additional future work could be as follows;

- Set requirements on product in terms of overall shape.
- Obtain inspection data in order to compare the real outcomes from manufacturing against predicted results from software.
- Further develop a RD&T fastener representing the IKEA wedge dowel.
    - Some suggestions on wedge dowel specific parameters have been given on this subject, but it could always be further developed according to IKEAs requests.
- Further investigate the resulting values gathered during non-rigid stress analysis in RD&T.

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APPENDIX A – CAD FILES EXPORT INSTRUCTIONS

When importing an assembly into RD&T, there is a risk that the positioning of the parts will be disordered. Because of this, it is of importance to keep the parts positioned correctly in the CAD software when exporting. If this is done, the parts will have the same position in RD&T when importing, which will make pre-work in RD&T easier. Also the accuracy of simulation results will be increased.

The following instructions shows an example on how to export files from the CAD-software SolidWorks and then import them into the CAT-tool RD&T, while keeping the assembled positioning intact.

- *Export assembly from Solidworks to RD&T (File → Save As)*
    - *The Top panel, bottom panel, 2 side panels, back panel and 2 drawer sub-assemblies should be exported as separate VRML files*
    - *Open the Product "Valje" (final assembly) in SolidWorks*
    - *Hide all parts but one (e.g. the top panel)*
    - *Select File → Save As*
    - *Select the file type VRML*
    - *Select an appropriate filename and save*
    - *Repeat this for all parts*

APPENDIX B – INSTRUCTIONS FOR CREATING SURFACE MESH SETS

RD&T can only use surface mesh to model composites material for e.g parts with several plies or sets. FEMAP and Abaqus/CAE was used to create surface mesh sets for this thesis Here follows step-by-step instructions for how this was done.

Step one: Extracting mid-surface
Extract mid-surfaces in FEMAP environment and export to Abaqus/CAE by using STEP file format.

Step two: Divide the surface geometry & create surface sets
Divide the surface into sets based on the Valje drawings contributed by IoS. The purpose of creating surface sets is to make selection of relative elements easy.

Step three: Mesh and mesh sets
After dividing the surface geometry and creating the surface sets, mesh the surface.
The element size can be determined by the user, but in RD&T a mesh size smaller than 5 mm can not give higher accuracy than using a mesh size of 5 mm.
The meshed surface sets can later be used for application of relative materials.

Step four: Export/modify .inp file
Create a “Job” in abaqus.Write input in that tab and export .inp file. If the elements in the defined sets are continuous, for example if an element set have 10 elements and these elements are continous from element 1 to 10, Abaqus will write the element set as ***Elset, elset="mesh 2", instance=Part-1-1, generate 1, 10, 1.** However, when RD&T reads mesh sets, it counts numbers as element numbers. This makes RD&T interpret this information as a mesh having 2 elements, element 1 (2 times) and element 10. There are basically two solutions to solve this problem. The first solution is to list all the elements in the set manually, which would be a great amount of work if there are a lot of elements in the set. The other solution is to delete this mesh set. RD&T will place all elements not included in a set in ”default set”. Then you can use this default set. However, there are limitations of using this default set. If there are two continous mesh sets in one surface mesh, this method can not be used since it will not be possible to define individual material parameters.

APPENDIX C – MATLAB CODE

Here the matlab code used to generate the graphical examples for C_p and C_{pk} are presented.

C.1 C_p

```
x = [-7:.1:7];
y = [0.5];
norm = normpdf(x,0,1);

figure;
hold on
plot(x,norm,'LineWidth',2)
plot([-6 -6],[0 max(y)],'-r','LineWidth',2)
plot([6 6],[0 max(y)],'-r','LineWidth',2)
plot([0 0],[0 0.4],'-g','LineWidth',2)

plot([-3 -3],[0 0.45],'-black','LineWidth',1)
plot([3 3],[0 0.45],'-black','LineWidth',1)

hold off

xlabel('Standard deviations - Sigma')
ylabel('Frequency')

text(-5.8,0.3,'LSL','FontSize',12)
text(6.2,0.3,'USL','FontSize',12)
text(0.2,0.1,'MEAN','FontSize',12)
text(-2.9,0.43,'<------   Process width   ------>','FontSize',12)
text(-5.92,0.48,'<---------------------------   Design width   --------------------------->','FontSize',12)
```

C.2 C_{pk}

```
x = [-7:.1:7];
y = [0.5];
norm = normpdf(x,1.5,1);

figure;
hold on
plot(x,norm,'LineWidth',2)
plot([-6 -6],[0 max(y)],'-r','LineWidth',2)
plot([6 6],[0 max(y)],'-r','LineWidth',2)
plot([1.5 1.5],[0 0.4],'-g','LineWidth',2)

plot([-1.5 -1.5],[0 0.45],'-black','LineWidth',1)
plot([4.5 4.5],[0 0.45],'-black','LineWidth',1)

hold off

xlabel('Standard deviations - Sigma')
ylabel('Frequency')

text(-5.8,0.3,'LSL','FontSize',12)
text(6.2,0.3,'USL','FontSize',12)
text(1.7,0.1,'MEAN','FontSize',12)
text(-1.4,0.43,'<------   Process width   ------>','FontSize',12)
text(-5.92,0.48,'<---------------------------   Design width   --------------------------->','FontSize',12)
```

Inspired by Burstein, L. (2015) *Matlab in Quality Assurance Sciences,* Elsevier, pg. 113-114