NordDesign 2022
August 16-19, 2022
Kgs. Lyngby, Denmark

Knowledge based engineering for formula student

Erik Nordvall[1], Mehdi Tarkian[2]

[1]Product Realisation, Department of Management and Engineering, Linköping University
erik.nordvall@liu.se
[2] Product Realisation, Department of Management and Engineering, Linköping University
mehdi.tarkian@liu.se

Abstract

The academic competition Formula student engage engineering students all over the world. In this paper, two applications of Design Automation (DA) and knowledge based engineering (KBE) are presented. Their purpose is to act as a proof-of-concept of time consuming, repetitive and error prone activities can be limited. Time and activities can instead be re-directed to value adding activities such as making more sustainable design decisions. Two applications are applied in the chassis design process. Each application is discussed and further steps and applications are presented.

Keywords: computer aided design (CAD), design automation, knowledge based engineering (KBE)

1 Introduction

Formula student is an academic competition in design and engineering. Using a motorsport context, students from universities around the world compete in engineering and entrepreneurial tasks to show that they have the best design and business plan. The task is to design a prototype single-seat open wheeled race car for autocross and sprint-racing whilst having to meet a strict deadline. The car is put through a number of dynamic and static test as well as technical inspection and scrutineering. The car is composed of many systems, such as the powertrain, the suspension and brakes, the aerodynamics and the drivers environment to name a few. The system connecting the systems together is the chassis.

Much like the other systems there are a lot of parameters to take into consideration when designing the chassis, such as rule compliance, manufacturing, cost, performance and system integration. The entire car is designed and manufactured during the year leading up to the competition. This strict time limitation leads to a very short and intensive design process in the beginning of the year. This early stage of the design process is where the design freedom is at its highest while the knowledge is at its lowest (Verhagen et al., 2012).

The design process for a formula student chassis is often rushed and the exploration of the design space is very limited. The need to iterate designs faster to make an active decision before moving to the detail design is clear. In addition, the members of the team are students from different years of study and in different fields. Most students are part of the team one year and then leave the team for the next generation of vehicle. Due to the limited resources of a formula student team, meeting all these parameters often results in a chassis that resembles a compromise between the parameters compared to an optimal solution. The rest of the technical systems that need to fit on the car have to take the chassis into consideration when designing their solution. In this paper, a method and framework for design automation of space frames and their welding jigs used in a racing context is explored and presented. The aim is to increase knowledge early in the design process where the design freedom is at its highest and to faster iterate feasible designs.

1.1 Goals

To reach a more efficient engineering process for formula student development, the following goals are proposed:

- G1 – Overview of the current design process of the formula student chassis by mapping out critical decisions criterion leading to the finalized designs as well as identifying repetitive processes.
- G2 – Based on the overview and identified pains, suggest an improved engineering process utilizing design automation and knowledge based engineering.
- G3 – Analysis and conclusion of how the proposed process can improve the engineering design process and what potential areas the suggested methods can be applied to.

1.2 Methodology

The following methodology outlines steps to accomplish the goals of this paper:

1. Analyze formula student rules for chassis design
2. Analyze the current way of working and what challenges are currently present in chassis design
3. Utilize methods within KBE and DA to automate processes and tasks in the chassis design process
4. Evaluate methods and implementations on the chassis design

2 Background

The following sections aim to outline the current design process, the common practices of space frame chassis design and competition rules that guide the design.

2.1 Chassis design rules

Examples of how geometric rules are applied. Material rules and the need for selection of materials. The chassis is a structure that supports all functional vehicle systems. A chassis member is a single piece of structure that makes up the chassis - such as a piece of tubing (Formula Student Rules, 2022) Node-to-node triangulation is used to ensure that each member is only subject to compressive or tensile forces by ensuring that the members meet at a node. For the scope of this paper the most basic components of an open wheeled chassis are:

Table 1. Summary of basic members that make up the main structure of a formula student frame.

Front hoop	A	Material type A
Front hoop bracing	B	Material type B
Main hoop	C	Material type A
Main hoop bracing	D	Material type B
Front bulkhead	E	Material type B
Front bulkhead supports	F	Material type C
Side impact structure	G	Material type B
Rear impact structure	H	Material type B
Rear side impact structure	I	Material type B

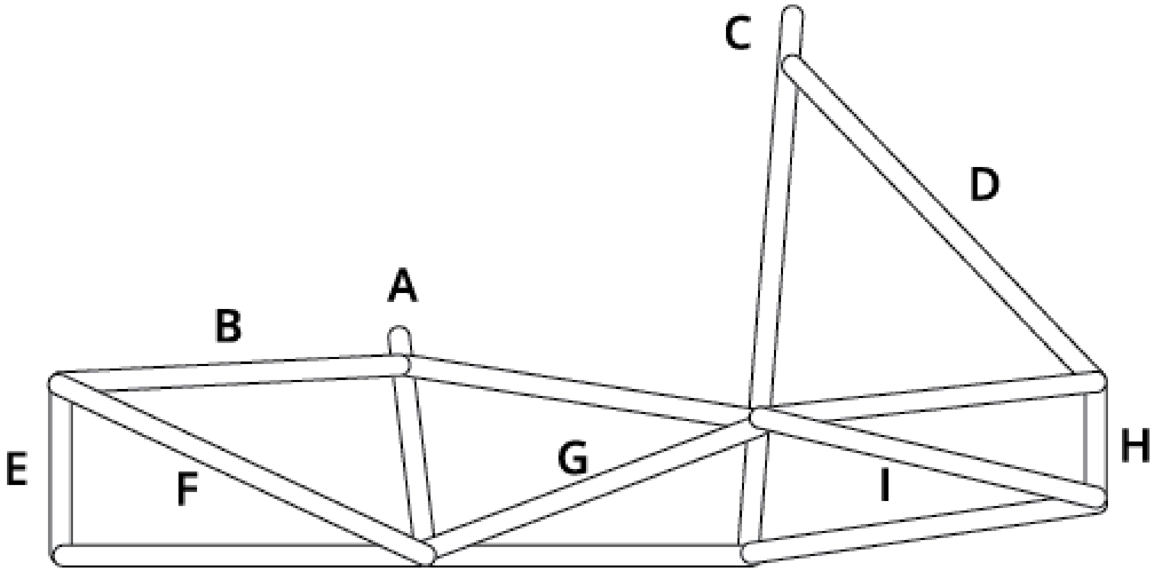


Figure 1. Side view of where structural members presented in table 1 are located.

2.2 Current design process

The current design process starts with fixed requirements and goals combined with a high level of uncertainty. Since most of the team is replaced each year and barely any knowledge management methods are used, the project starts off by focusing on making it to the competition. The car itself has its own design process where requirements and goals are set. These requirements are tied to what type of general systems will be in the car, such as what type of powertrain, electric or combustion. What size will the car be, will it have an aero package, what does the budget allow, what sponsors are feasible for this year etc. These types of requirements together with the rules lay the foundation for each system designer.

On a system level, a new concept development phase is initialized. Depending on the system, this step varies in length. Each system has different design activities and different deadlines. Some systems have a lot to copy from previous years, and some have to start over. To ensure that all components can be manufactured in time, there are design gates where certain design requirements and concepts need to be specified and are locked in. The final deadline for the design is known as the ’CAD-Lock’. After this date, no CAD changes should be made and the focus shifts from design to manufacturing. The time frame from the first meeting with each system team to CAD-lock is three months.

Currently, the design that is locked after three months is the same as the first design concept. There is rarely time to iterate, analyze or generate other concepts, resulting in a poor design in some cases and often realized when it is too late to change.

The focus of this paper is the design and manufacturing of the chassis system. The chassis system has a very short design process. Each subsystem tied to the chassis need to know the placement of all members in the chassis to know where they can place their components. Currently the process looks like the following:

- **Material selection –** Before designing the actual members of the frame, available material must be investigated and selected. The material is very similar each year. A check for suitable steel and suitable dimensions of tubes that fulfill the material requirements set by the rules while steel being able for purchase and with a suitable delivery date is determined.

- **Front hoop & main hoop –** The next step is the design and placement of the front hoop and the main hoop. The distances from the front of the car are set and the angles of the hoops. The hoop placement is important for the entire structure car as it determines the available space for other systems such as the powertrain and attachments for wings, thus the placements and angles need to be set early in the process. The driver ergonomics and field of vision are important factors to consider when setting angles of the hoops. The drivers field of view should not be limited by the height of the front hoop, while at the same time a suitable driving position needs to be set by the angle and distance to the main hoop. Currently low-level mock-ups for angles are done occasionally but are far from accurate or routine-like.

- **Hoop bracing & impact structures –** A very important structural design step is to ensure that the hoops are securely tied into the frame in the case of a crash. There are strict rules provided for how this is to be done. In addition, impact structures on the front, rear and on both sides of the drives are added for further safety. Together with the hoops, these members make up the main structure for the frame. At this point all structural members required from the rules have been added.

- **Suspension mounting points –** The mounting points for the suspension are where most of the mechanical loads are but on the chassis. These points are provided from another subsystem working with the suspension design for the car. At this stage, the mounting points are usually not set in their final location as that team is also going through a design process.

- **Additional members –** Members that are non-structural according to the rules are added to the frame in this step. For example, members allowing for the mount of motors, batteries or other powertrain components. Further, floor tubes are added in this step to allow the driver climb in and out of the car, pedals and seats to be mounted and provide some extra stiffness to the frame.

- **Calculation and analysis –** The important calculations made on the chassis is the stiffness. The design of the frame makes sure that it fits in with all other structural requirements set by the rules of the Formula Student competition, so no further structural analysis needs to be done. The stiffness is used to ensure that the frame is sufficiently stiff for performing as intended. Due to the compact timeframe, this stage is almost last. It is not ideal since if the analysis shows that the frame is not performing well, changes are very limited at this stage.

- **Tube notching & manufacturing preparation –** One of the most repetitive and error prone tasks is the tube notching and manufacture preparation step. In order for the frame to be welded, all tubes have to be notched with respect to each other. Not only notching to all other tubes in contact but the tubes have to be notched in the order they will be welded so that no tube relies on a joint that is not present at the time of welding. Each tube is notched manually using a built-in tube notching tool. Weld gaps are also added to the notches to allow the welding process to be sped up. It is very time consuming and can take up to 3 weeks of the entire process. In addition, the information gap from previous years makes this difficult process the subject of many errors that reveal themselves only when the frame needs to be welded. The tubes are laser cut in a tube laser at a different location and finished tubes are picked up 4-5 weeks after the CAD is finished.

- **Welding jig design and assembly –** Another large part the manufacturing preparation stage is the design of the weld jig. Currently this process in manual and each design decision needs to be carefully considered. The jig is made from wood and holds the frame members in place when welding. This process is very time consuming and is commonly rushed. The quality of the jig varies from year to year making it difficult to get consistent manufacturing quality and development of the jig.

2.3 Identified pain

The identified pains of the current design process are the following:

- Time consuming processes such as manually identifying all rules and checking rule compliance at all stages. Further, manually doing notching work and CAD construction of the welding jig.
- Repetitive processes such as for each member creating a profile and manually creating each member in the chassis. Searching for suitable materials each year.
- Error in processes such as many manual processes, prone to human error. Errors that occur due to inconsistent processes and lack of knowledge.
- Non-sustainable processes such as wasting time re-doing tasks when changes must be made. In addition, errors discovered late in the manufacturing stage lead to waste of materials as they need to be discarded.

3 Design automation & Knowledge based engineering

Design automation (DA) is an area of study with the focus of automating routine and non-creative parts of the design process. The implementation of knowledge based engineering (KBE) as a means to effectively capture knowledge by storing rules, relations and facts is a step towards Design Automation. (Amadori et al., 2012).

Chapman & Pinfold (2001) refer to KBE as "an engineering method that represents a merger of object-oriented programming (OOP), artificial intelligence (AI) technology and CAD (Chapman & Pinfold, 2001) In this paper the Design Automation focus is on creating and analyzing 3D geometries. In some design projects, up to 80\% of all manual design activities are repetitive and routine like (Stokes, 2001).

A methodology similar to Stokes MOKA is applied in this paper. The methodology consists of the following four activities: Problem identification, Knowledge capture, Knowledge formalization, and Framework development & Test.

4 Applications

Two applications have been implemented an evaluated for this paper. These are presented in the following sections.

4.1 Analysis driven structural design

The implementation of the three main parts of the framework was done using CATIA v5, Microsoft Excel and ModeFrontier. The initial 3D geometry is set up in CATIA v5 using points and lines to create a wireframe structure. The hoops are sketches on separate planes, made of from 7 points with arcs to create the bends. An image showing the frame in CATIA V5 can be seen in figure 8. The design parameters set by the user is set in the graphical interface. The different tubes available for use is also set up in the graphical interface. The optimization is set up in ModeFrontier to change the positions of the nodes, the hoop sketches and the angles of the planes for the sketches. Prior to the stiffness calculation, there is an initial rule compliance check done in excel. The purpose is to save computational time by terminating an optimization early if the 3D geometry of the chassis violates any rules. For example the radius of the bends in the hoops have to be three times as large as the outer diameter of the tube. Depending on how large the tube is, the allowed radius of the bend can change.
The stiffness calculation is done in CATIA v5 and the parameters for the stiffness calculation is taken from the user inputs in the graphical interface. The trackwidth and the wheelbase of the car are the key inputs for setting up the longitudinal torsional stiffness calculation. The final calculation of the stiffness is done in ModeFrontier. The output from CATIA v5 is the displacement and the maximum stress at 1000N applied at each wheel center using a remote force. The torsional stiffness is calculated by dividing the applied force by the displacement angle. The maximum stress is used to determine if the design will break or not.

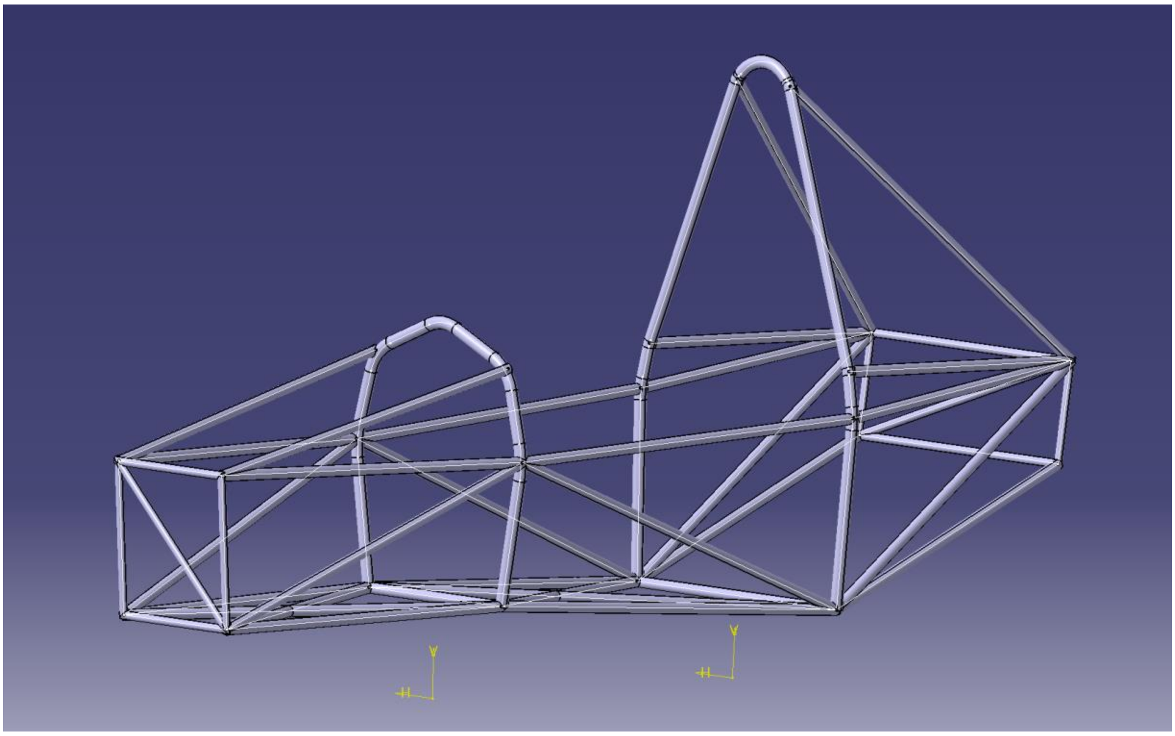


Figure 2. Figure showing the structural members used for structural analysis of the frame.

Figure 2 and 3 shows the difference between the key members needed for construction and a fully constructed chassis with all additional members and suspension points. The members placed in figure 2 make up the shape of the entire chassis and take out a large part of the initial design stage.

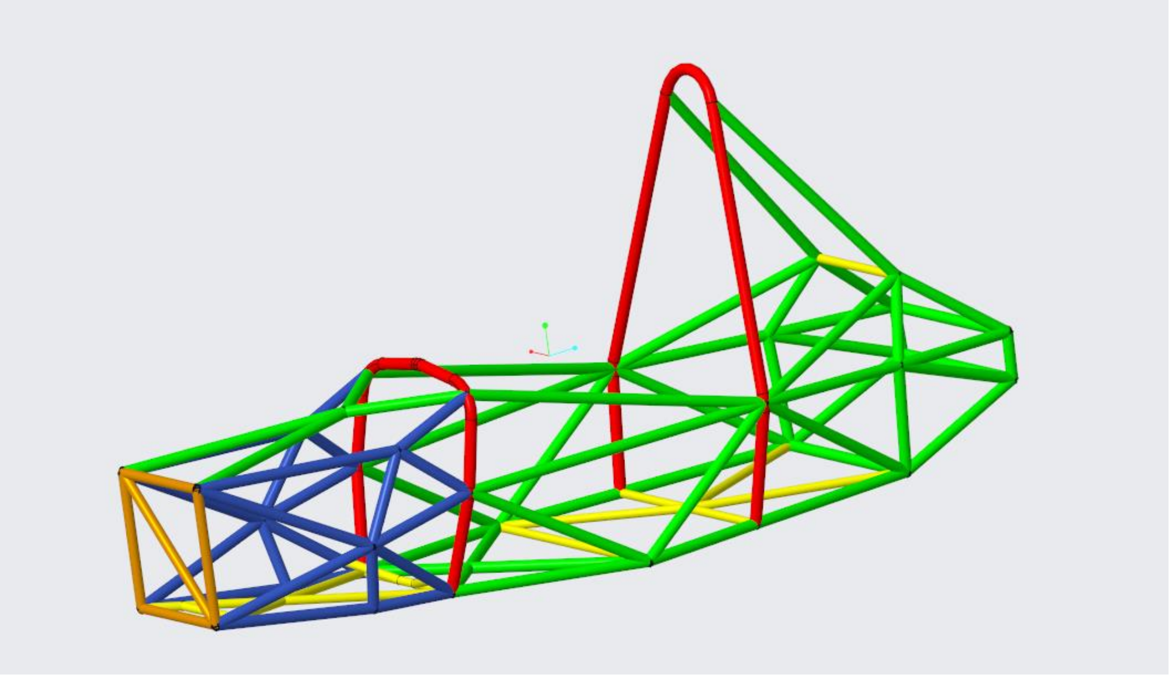
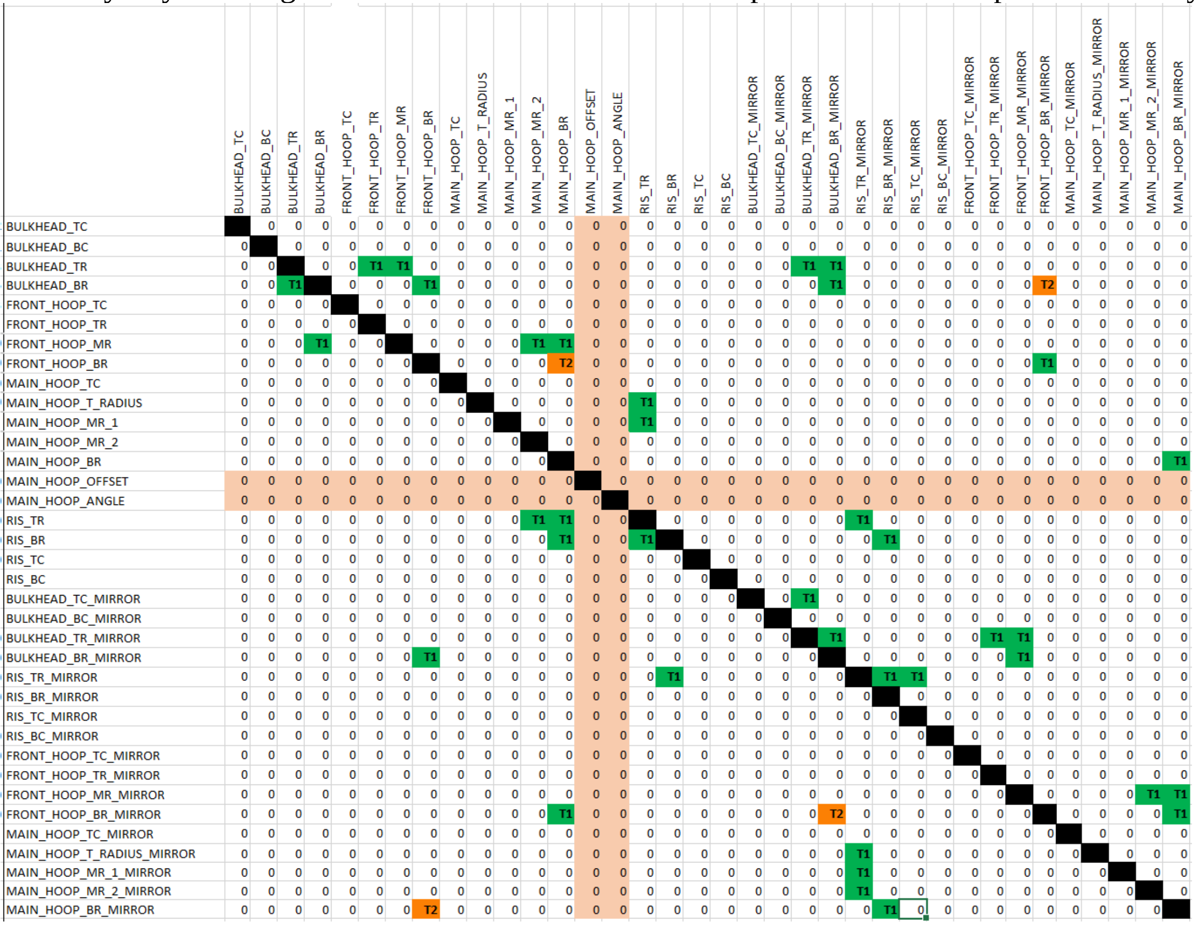


Figure 3. Example of completed space frame chassis. Each colour represents a different type of tube.

4.2 Wireframe driven weld jig

Similar to the previous application, the construction of the welding jig is done in CATIA v5 and controlled though rule based scripts in Microsoft Excel. The jig is designed to fit around any wireframe geometry and from the same material thickness and can be seen in figure 4.The jig can be instantly constructed around the wireframe and updates if geometry adjustments need to be made, without manually having to redesign the jig. The rules for the jig allows it to be built layer by layer, starting with the bottom tubes. The next layer is made up from perpendicular pieces with cutout for the middle members. These perpendicular parts are placed manually by writing the distance for where the part should be placed. Finally, the top layer is created automatically between the vertical pieces to add rigidity to the structure and support members that are high up, such as the main hoop bracing.



	BULKHEAD_TC	BULKHEAD_BC	BULKHEAD_TR	BULKHEAD_BR	FRONT_HOOP_TC	FRONT_HOOP_TR	FRONT_HOOP_MR	FRONT_HOOP_BR	MAIN_HOOP_TC	MAIN_HOOP_T_RADIUS	MAIN_HOOP_MR_1	MAIN_HOOP_MR_2	MAIN_HOOP_BR	MAIN_HOOP_OFFSET	MAIN_HOOP_ANGLE	RIS_TR	RIS_BR	RIS_TC	RIS_BC	BULKHEAD_TC_MIRROR	BULKHEAD_BC_MIRROR	BULKHEAD_TR_MIRROR	BULKHEAD_BR_MIRROR	RIS_TR_MIRROR	RIS_BR_MIRROR	RIS_TC_MIRROR	RIS_BC_MIRROR	FRONT_HOOP_TC_MIRROR	FRONT_HOOP_TR_MIRROR	FRONT_HOOP_MR_MIRROR	FRONT_HOOP_BR_MIRROR	MAIN_HOOP_TC_MIRROR	MAIN_HOOP_T_RADIUS_MIRROR	MAIN_HOOP_MR_1_MIRROR	MAIN_HOOP_MR_2_MIRROR	MAIN_HOOP_BR_MIRROR
BULKHEAD_TC		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BULKHEAD_BC	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BULKHEAD_TR	0	0		0	0	T1	T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1	T1	0	0	0	0	0	0	0	0	0	0	0	0	0
BULKHEAD_BR	0	0	T1		0	0	0	T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	T2	0	0	0	0	0
FRONT_HOOP_TC	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FRONT_HOOP_TR	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FRONT_HOOP_MR	0	0	0	T1	0	0		0	0	0	0	T1	T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FRONT_HOOP_BR	0	0	0	0	0	0	0		0	0	0	0	T2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	0	0	0
MAIN_HOOP_TC	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAIN_HOOP_T_RADIUS	0	0	0	0	0	0	0	0	0		0	0	0	0	0	T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAIN_HOOP_MR_1	0	0	0	0	0	0	0	0	0	0		0	0	0	0	T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAIN_HOOP_MR_2	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAIN_HOOP_BR	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1
MAIN_HOOP_OFFSET	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAIN_HOOP_ANGLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RIS_TR	0	0	0	0	0	0	0	0	0	0	0	T1	T1	0	0		0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	0	0	0	0	0
RIS_BR	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	T1		0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	0	0	0	0
RIS_TC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RIS_BC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BULKHEAD_TC_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BULKHEAD_BC_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BULKHEAD_TR_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		T1	0	0	0	0	0	T1	T1	0	0	0	0	0	0
BULKHEAD_BR_MIRROR	0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	T1	0	0	0	0	0	0
RIS_TR_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	0	0	0	0		T1	T1	0	0	0	0	0	0	0	0	0	0
RIS_BR_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
RIS_TC_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0
RIS_BC_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0
FRONT_HOOP_TC_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
FRONT_HOOP_TR_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
FRONT_HOOP_MR_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	T1	T1
FRONT_HOOP_BR_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	0	0	T2	0	0	0	0	0	0	0		0	0	0	0	T1
MAIN_HOOP_TC_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
MAIN_HOOP_T_RADIUS_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	0		0	0	0
MAIN_HOOP_MR_1_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	0	0		0	0
MAIN_HOOP_MR_2_MIRROR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	0	0	0		0
MAIN_HOOP_BR_MIRROR	0	0	0	0	0	0	0	T2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	T1	0	0	0	0	0	0	0	0	0	0	

Figure 4. Figure showing the connection matrix for all the nodes in the frame.

Once the design is finished for the jig, the parts can be exported automatically to be manufactured in a 2D CNC mill or laser cutter.

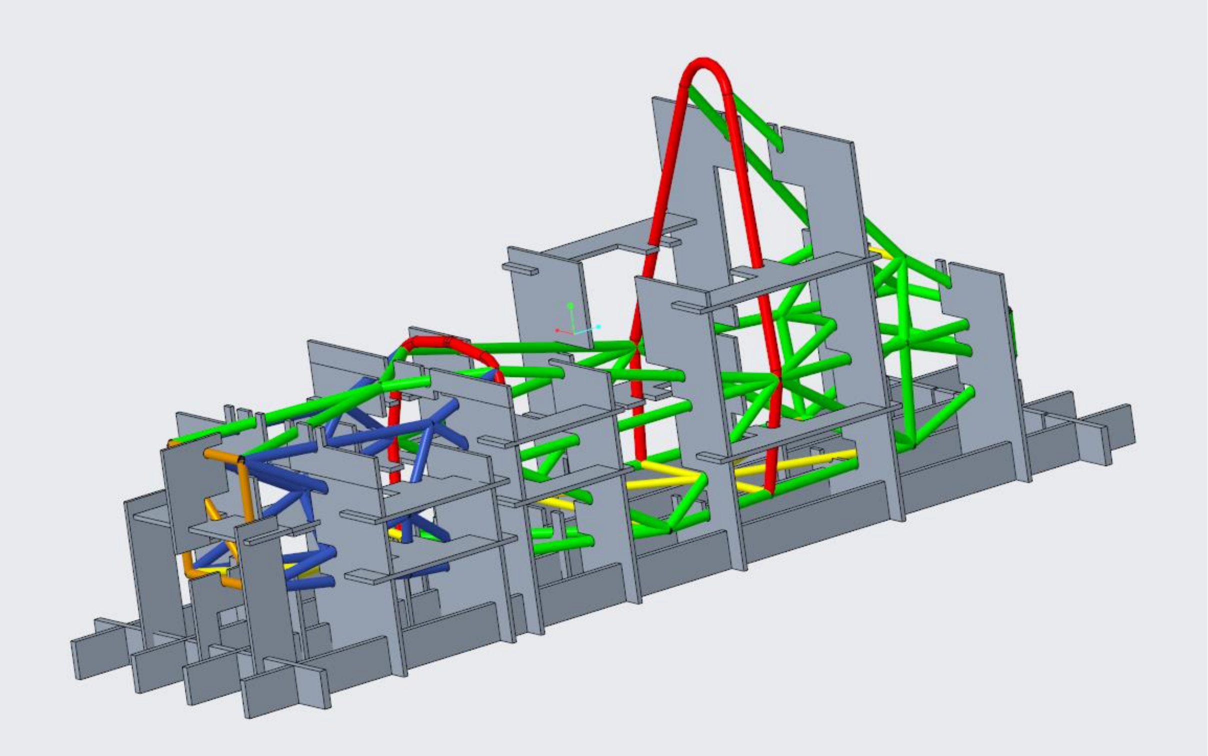


Figure 5. Figure showing the result of the automatic jig builder based on the wireframe of a complete frame design.

5 Discussion

By saving time in the beginning of the design process, activities that are currently disregarded due to a lack of time can be developed and the quality of the vehicle can increase. For example, driver ergonomics are not considered and issues arise when the car is manufactured, and the driver sits in the car for the first time. With additional time for changes in the beginning, ergonomic models can be used to maximise the drivers potential when racing.

In addition, the current DA framework only generates the essential members of the chassis and not all members. By developing the DA framework further and incorporating the suspension mounting points and different controls for where the floor can be placed, then the entire chassis design could be automated, saving more time in the initial stages.

A large part of the points in the competition come from the quality of the design. By automating non-creative and non-competitive parts of the design, focus can be shifted to more value adding activities of the design process making the team more competitive.

By standardising the weld jig and creation of manufacturing files, the uncertainty for errors will go down significantly. Not only will this allow for the ‘CAD-lock’ to be pushed closer to the start of manufacture, allowing for a longer design process, but also makes a more sustainable and less wasteful manufacturing process. For example, tubes come in standard lengths and by optimally placing out what members are lasered from which tube, then the waste material can be mitigated. Similarly for the manufacturing of the welding jig, the 2D parts can be placed on a sheet and optimised for minimal waste.

The aim of this paper is to show a possible implementation of design automation frameworks including a user interface, 3D geometry and optimization. The focus has been on the chassis system as a proof of concept. However, the same pains identified in this paper apply across all mechanical parts of the car. By implementing a similar KBE MOKA method and DA approaches, substantial gains in time and quality can be had in all subsystems. Not only will this increase competitiveness but make each year's design decisions more thought through and reusable for the future of the teams. Time consuming processes, repetitive processes, errors in processes and non-sustainable processes have been automated and identified pains within these areas have been reduced.

6 Conclusion

Applications of DA and KBE show that the identified pain of time consuming, repetitive error prone and non-sustainable processes can be alleviated in the design process of a formula student chassis. Time consuming processes have been automated to condense the design process. Repetitive and error prone processes can be eliminated to allow for more value adding activities with focus on increasing competitiveness and sustainable, lasting design decisions. This paper has shown a practical application of KBE and DA in formula student context and justified its potential through mitigating identified shortcomings in the current design process.

Further applications in the design process of the formula car in its entirety has the potential to evolve the team in to making more rapid design changes and taking greater development leaps each year.

Acknowledgement

Special thanks to Thijs Hobbenschot, Victor Hjärpe and Victor Hjort for their work on the automatic welding jig in the course TMKU01 at Linköping University. Also thank you to Emil Lundberg (Chassis Team Leader of LiU Formula Student 2022) for participating in discussions.

Citations and References

Amadori, K., Tarkian, M., Ölvander, J., & Krus, P. (2012). Flexible and robust CAD models for design automation. Advanced Engineering Informatics, 26(2), 180–195.

Chapman, C. B., & Pinfold, M. (2001). The application of a knowledge based engineering approach to the rapid design and analysis of an automotive structure. Advances in Engineering Software, 32(12), 903–912.

Stokes, M., 2001. Managing Engineering Knowledge; MOKA: Methodology for Knowledge Based Engineering Applications, first ed. Professional Engineering Publishing.

Verhagen, W. J. C. et al. (2012) 'A critical review of Knowledge Based Engineering: An identification of research challenges', Advanced Engineering Informatics, 26(1), pp. 5–15. doi: 10.1016/j.aei.2011.06.004.