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MULTI-OBJECTIVE OPTIMIZATION OF HOSE ASSEMBLY ROUTING FOR VEHICLES

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Abstract

This paper presents a method for multi-objective optimization of hose assembly routing. Hose routing is a non-trivial task which demand a lot of iterations, especially with the increased complexity in modern vehicles. The proposed method utilizes design automation through multi-objective optimization of routing assemblies containing multiple hoses. The method is intended as a decision support and automation-tool, that reduces the number of iterations needed. The method has been implemented and tested on a case, concerning a set of hoses in an engine compartment, showing credible results.

Keywords: design optimisation, design automation, knowledge-based engineering (KBE)

1. Introduction

There is a trend in industry to develop more complex products combining technologies from diverse disciplines in tight integration within a confined geometrical space. This is particularly true in vehicle applications such as aircrafts, ships and cars. One such example is the design of modern cars where there are many components from diverse disciplines that need to compete for the same physical space. When designing the routing of hoses in the engine compartment of a vehicle, such as air and fuel pipes and electrical wires, design engineers are often dealing with many conflicting objectives. Modern vehicles are complex and integrated products containing electrical systems and sensors integrated with mechanical components and actuators. There are many parameters to take into consideration in the development process of the hose routing such as material cost, performance, production and assembly aspects and durability as well as surrounding geometry with sharp edges or hot surfaces. All in all, this often means that there is no obvious solution for the routing of multiple hoses assembled in the same, often already densely packed, space**.** This leads to many iterations and repetitive work in the development process, demanding a large amount of resources and organizational coordination. There are various tools available used in industry to aid the development process of hose routing; one of them being the software Industrial Path Solutions (IPS) which provides path planning, simulations of flexible structure and assembly verification among other things (Fraunhofer Chalmers Centre, 2019). These tools are useful for routing single hoses one at a time and to evaluate hose assemblies with various simulations, but are lacking support to deal with trade-offs for multiple hoses.
In this paper, a proposed method and framework for design automation and multi-objective design optimization of hose routing assemblies is presented. Design automation is a methodology for automating parts of the product development process that are repetitive (Amadori, 2012), while design

optimization is a method for finding and evaluating design alternatives using numerical optimization algorithms (Andersson, 2000). The product development process is often described by various process models and a wide range of different models have been categorized by Wynn and Clarkson (2018). Many process models include conceptual design stages that come prior detailed design stages (Pahl and Bietz, 1996; Ulrich and Eppinger, 2012; Pugh, 1991). It is in these early stages that the design freedom is at its highest while the knowledge about the product is at its lowest (Verhagen et al., 2012). One way to increase the knowledge is to use design optimization which can help engineers to make informed decisions and explore the design space when the freedom is at its highest. The decision making by the engineers play an important role in multi-objective design optimization (Sobieszczanski-Sobieski et al., 2015) and tools developed for incorporation and augmenting of engineering capabilities have been stated as an important aspect of future (multidisciplinary) design optimization research (Simpson and Martins, 2011). The utilization of design automation and optimization in the proposed method enables automatic generation of a set of optimized hose routing assemblies where multiple objectives are considered in the conceptual stages of the development process, which can be taken further into the detailed design phases of the development process. The framework is intended to act as a decision supporting tool to aid the engineers, increase the knowledge, decrease the numbers of iterations needed and to automate repetitive tasks in the development process.

This paper is divided into the following sections; first a background containing theory and description of common practice of hose routing in vehicles. Then the proposed method is presented describing the main steps of the method and its intended use and contribution, including a description of the optimization framework. Next, results from an implementation of the framework tested on a case are presented. This is then followed by a discussion and last some conclusions.

2. Background

Design automation and design optimization are methodologies for aiding the product development process that have been utilized in the proposed method in this paper. These are described in the following sections followed by a description of common practice of hose routing in industry and theory which routing algorithms build upon.

2.1. Design automation

The concept of design automation aims at automating parts of the design and development process that are repetitive, which according to Stokes (2001) could occupy up to 80% of engineering activity. CAD is often associated with design automation, where both morphological and topological parameters in the CAD model can change (Amadori et al., 2012) given certain input in a design automation model. The translation between the input and the generation of the design can be achieved using Knowledge Based Engineering (KBE), which by La Rocca (2012) is defined as a technology for automating repetitive and non-creative tasks by systematic capture and reuse of product and process engineering knowledge with the aim of reducing time and cost of product development. In particular, the opportunities of successful KBE implementations lie in the early stages of the product development process where the design freedom is at highest and the largest percentage of the product's life cycle cost is committed (Verhagen et al., 2012). About a decade ago, it was stated that the future intelligent CAD systems with knowledge bases were facing some challenges for success such as connection and integration with existing CAD systems and adaption to changes in the daily re-design activity, meaning they need to be developed as a part of the product development process (Tomiyama, 2007).

2.2. Design optimization

Design optimization is a method used to support the product development process, in terms of both efficiently and effectively finding the desired design of a product. This can mean finding the dimensions of a component that has the lowest possible cost but still satisfies requirements for mechanical strength. Design characteristics, for example cost, are formulated as mathematical expressions that consititute the objective function of the optimization, which often in real-world engineering problems contains a set of

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characteristics such as material weight and manufacturing cost (Sobieszczanski-Sobieski et al., 2015). Such optimization problems, where more than a single objective is considered, are referred to as multi-objective optimization (MOO) problems. In MOO problems, there exists no single optimal solution, and oftentimes, the objectives are conflicting, such as cost and material strength. Those optimization problems then result in inevitable trade-off designs, also called Pareto optimal design, where Pareto optimality means that for the Pareto optimal points in the feasible design space, there is no other point where an objective can be improved without deterioration of at least one other objective (Chang, 2015). Here, the engineer has the task of selecting the best design based on the relative importance of the objectives (Sobieszczanski-Sobieski et al., 2015).

One category of optimization algorithms are evolutionary algorithms which are mimicking nature such as ant colony optimization (ACO) and multi-objective genetic algorithm (MOGA), for which improved versions have been developed such as MOGA-II. Genetic algorithms have been successfully applied to a wide range of engineering problems and can robustly handle a mixture of real and discrete variables (Andersson, 2000). The general idea of genetic algorithms is to mimic natures evolutionary process, by creating populations of individuals, where each individual represents a single design solution. The individuals are constructed by genes that represent design variable values. The population evolves by creating offspring individuals combined from the fittest individuals from the previous generation, hence creating an artificial evolutionary process of survival-of-the-fittest. Since these algorithms create a population of solutions, they are well fitted for MOO problems, because they are able to find multiple pareto-optimal solutions in a single optimization run (Ghosh and Dehuri, 2004).

2.3. Path planning and hose routing

Path planning and hose routing is a comprehensive field of research. Since automatic hose routing builds on path planning algorithms, which in complete form are computationally complex and slow, they are of little industrial relevance (Hermansson, 2017). Many various methods and algorithms have been developed and applied for solving various types of pipe, wire and hose routing for example evolutionary algorithms such as MOEA/D, a variant of multi-objective evolutionary algorithm developed by Li and Zhang (2006), applied on branch pipe routing (Liu and Liu, 2018) and ACO applied on multiple pipe and hose routing (Thantulage, 2009; Qu et al., 2018) and with constrained sampling (Kabul et al., 2007) but with limitations due to computational cost. Hermansson et al. (2016) developed a path planning two-step method for deformable objects where the optimal collision free path is found first, followed by a locally optimized simulation to ensure static equilibrium of the object.

A common strategy for routing hoses today in industry is to define the initial problem by setting up the conceptual assembly of the hoses in a CAD environment. This is often done in stages when multiple hoses are to be routed in the same area, typically by several engineers within several departments, responsible for different hoses. In the following step, evaluations of the hose assembly are usually done with the support of simulations of for example gravitation, stress and dynamics. Usually, from the results of the simulation-based evaluation, the assembly of the hoses are adjusted and re-simulated. This process is iterated until an acceptable final solution is found. The hoses are often manufactured with pre-formed bends to ensure shape and thereby quality of the hose routing. In some cases, various coupling devices are integrated in the assembly, to manipulate the direction of the start and end nodes of the hoses and thereby resolve complex situations. Another way to ensure quality and solve complex cases is to use clips to attach the hoses on other components, or to attach hoses to each other.

Software for aiding the development process are useful for routing single hoses one at a time, but are less useful for routing of multiple hoses concerning the trade-offs between them, but can be used for simulations of the complete hose assembly. Industrial Path Solutions (IPS) is one such software that provides path planning, simulations of flexible structure and assembly verification among other things (Fraunhofer Chalmers Centre, 2019).

3. Proposed method

The method proposed in this paper includes a design automation and optimization framework for hose routing assemblies which can provide an acceptable start solution taking several disciplines into

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account simultaneously. The solution generated from the framework will still need adjustments and modifications from the engineers but can reduce the number of iterations needed before the final solution. Hose routing is a complex and time-consuming engineering problem and it seems hard to find a complete solution without need for further adjustments. Referring to a generic product development process, such as the one by Ulrich and Eppinger (2012), the proposed method would fit into the system-level design stage, where the aim would be to generate a hose routing assembly which can initiate the detail design stage, as seen in Figure 1.

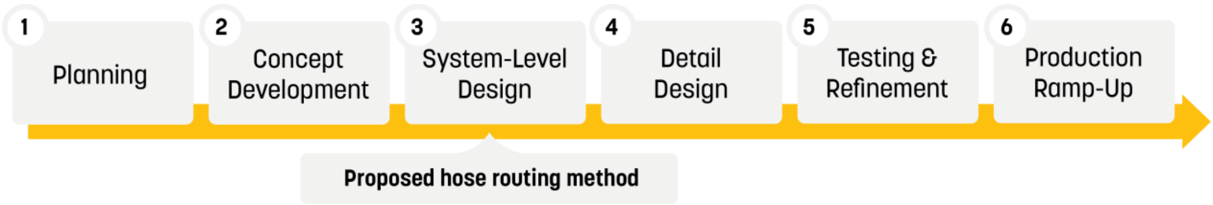

Figure 1. Hose routing in a generic product development process

3.1. The optimization framework

The foundation of the optimization framework is a design automation framework, which can also be used as a standalone tool. The design automation framework consists of three main parts; the CAD geometry, a graphical user interface and the hose simulation, as seen in Figure 2. First, the surrounding geometry where the hoses are to be routed in is set up in CAD, in terms of setting out points in the model representing start and end nodes of the hoses, indicating the nodes from which fluid is to be transported, e.g. liquid from the cooler to the engine. Next, an interface is used to import the CAD-data, for setting up requirements for the hoses, e.g. in terms of their cross-section radiuses, setting the order in which they should be routed, and defining which points the hoses should be routed from, to and through. Then, the automated routing is initiated through the interface, and is simulated on gravitation and stress in a simulation environment. The simulation software is able to route only one hose at a time, searching for a collision free optimal path. Consequently, for the routing of each hose, the previously routed hoses are added to the surrounding geometry to prevent collision between the hoses. This means that the order in which the hoses are routed will affect the overall result of the routing assembly. From the simulation environment, routing results are obtained in terms of characteristics and measurements of the routing such as length of the hoses, maximum stress of each hose as well as clearances between the hoses and, if desired, clearance to specific chosen components such as hot surfaces etc. The measurement values are imported to the interface where they then can be reviewed and evaluated and also used to formulate objective functions for the optimization.

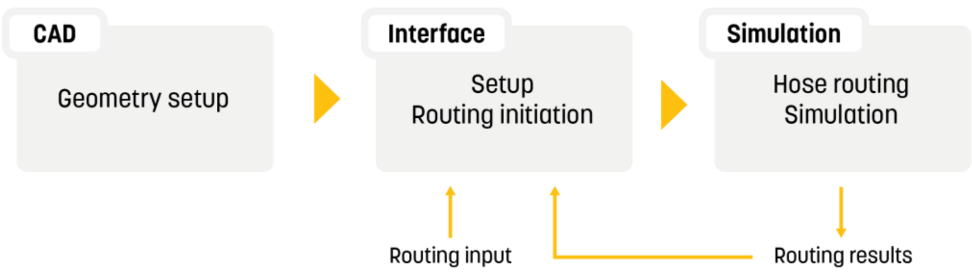

Figure 2. The building blocks and process of the design automation framework

Added to the design automation framework is an optimization driver, enabling multi-objective optimization searching for the optimal configuration of the hose routing assembly by varying the routing input. The optimization framework can be seen in Figure 3. Through an optimization algorithm, the routing input is controlled, meaning that the optimization sets the order in which the hoses are routed and through which points they are drawn. Based on the routing results, that consists of the total material volume for the hoses in the assembly in terms of, maximum stress in any of the

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hoses and the minimum clearances between the hoses and the surrounding, the routing input is adjusted in the optimization algorithm. The objectives are to minimize the total volume, for cost purposes, and to minimize the maximum stress and maximize the clearances, for performance and durability purposes. A more thorough description of the problem formulation and the variables follows in the next sections. The result of an optimization run is a set of pareto optimal hose assembly solutions, which can be reviewed by the engineers and used in the next detail level design phase in the development process.

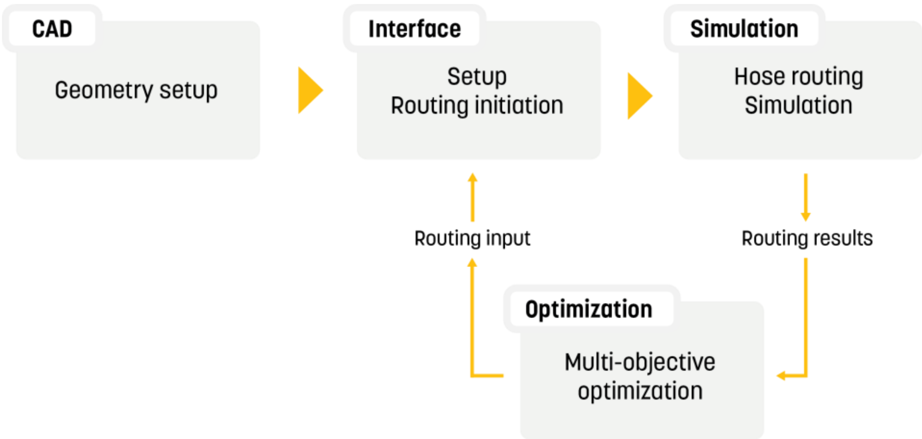

Figure 3. The building blocks and process of the optimization framework

3.2. Problem formulation

The optimization problem is a non-linear multi-objective optimization problem containing both discrete and continuous variables (Equations 1-5). Four objectives are used in the optimization framework and can be formulated as:

$$min \begin{cases} f_1 = sum(V_i(\bar{x}, y), \ldots, V_n(\bar{x}, y)) \\ f_2 = max(\sigma_i(\bar{x}, y), \ldots, \sigma_n(\bar{x}, y)) \end{cases} \quad (1)$$

$$\max \begin{cases} f_3 = clearance_{between\ hoses}(\bar{x}, y) \\ f_4 = clearance_{to\ component}(\bar{x}, y) \end{cases} \quad (2)$$

subject to:

$$1 \leq y \leq n! \quad (3)$$

$$\bar{x} = \begin{bmatrix} x_{1,1} & \cdots & x_{1,j} \\ & \vdots & \\ x_{i,1} & \cdots & x_{i,j} \end{bmatrix} = \begin{bmatrix} r_{1,1} & \theta_{1,1} & \varphi_{1,1} & \cdots & r_{1,p} & \theta_{1,p} & \varphi_{1,p} \\ & & & \vdots & & & \\ r_{n,1} & \theta_{n,1} & \varphi_{n,1} & \cdots & r_{n,p} & \theta_{n,p} & \varphi_{n,p} \end{bmatrix} \quad (4)$$

$$0 \leq x_{i,j} \leq 1,\ i = 1 \ldots n,\ j = 1 \ldots 3p \quad (5)$$

where V_i is the volume of hose i and σ_i is the maximum stress of hose i. n is the number of hoses and p is the number of via-points. y is an integer variable between 1 and $n!$ that points to a specific permutation that decides in which order the hoses should be routed. The first objective f_1 is to minimize the total volume of the hoses in the assembly, the second objective f_2 is to minimize the highest measured stress of any of the hoses, the third objective f_3 is to maximize the minimal clearance between the hoses whereas the fourth objective f_4 is to maximize the clearance between the hoses and one of several specified critical components. A critical component could be a hot surface or a sharp edge, which benefits from extra clearance and needs additional monitoring. $\bar{x}$ is the variable in the optimization, which decides the placements of the via-points defined by three values for each via-point; r_i, θ_i and φ_i. A via-point in this context means a point in the model that the hose should be routed through between the start and end nodes, like a waypoint. This variable is described in more detail in the next section. Designs where collision-free paths for all hoses in the assembly are not found are considered unfeasible.

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3.3. Pre-forming with via-points

The use of via-points, and more specifically the placement of them, as optimization variables represents pre-forming of hoses. Pre-forming is usually a design choice made by the engineers to ensure shape and quality of the hoses, as earlier described in section 2.3. The use of via-points in the optimization framework enables the optimization algorithm to find routing compromises in order to obtain globally optimized assemblies. Adjustment of the routing path through the use via-points of one hose can allow for the next hose to find a better routing path leading to a better overall assembly. The routing path of each hose is locally optimized, but constrained by the globally optimized via-points. In other words, for each hose the routing algorithm in the simulation software will try to find the optimal path, given both the surrounding and the points that has to be passed through.

The framework has been developed for optimization of the placement of either one or two via-points per hose. The placement of them is defined within a design space in the shape of a sphere. The spheres definitions are described in the next section.

3.3.1. Placement of the via-points

In the case with one via-point for each hose, the space where the via-point can be placed is within a sphere that has the centre at the midpoint of the two nodes of the hose, and its radius as large as the shortest distance between the start and end node. When two via-points per hose are used, the spheres where the via-points can be placed are instead defined with the centre at each start and end node, and the radius is half the distance between the nodes. Examples of both cases can be seen in Figure 4. The placement of the via-point in the sphere is controlled with three parameters; r, θ and φ which are factors from 0 to 1. 0 in the radius-factor r would place the via-node at the centre of the sphere and 1 would place it on the edge of it. Azimuth- and altitude-factors θ and φ decides the rotation of the placement around the axes at the centre of the sphere.

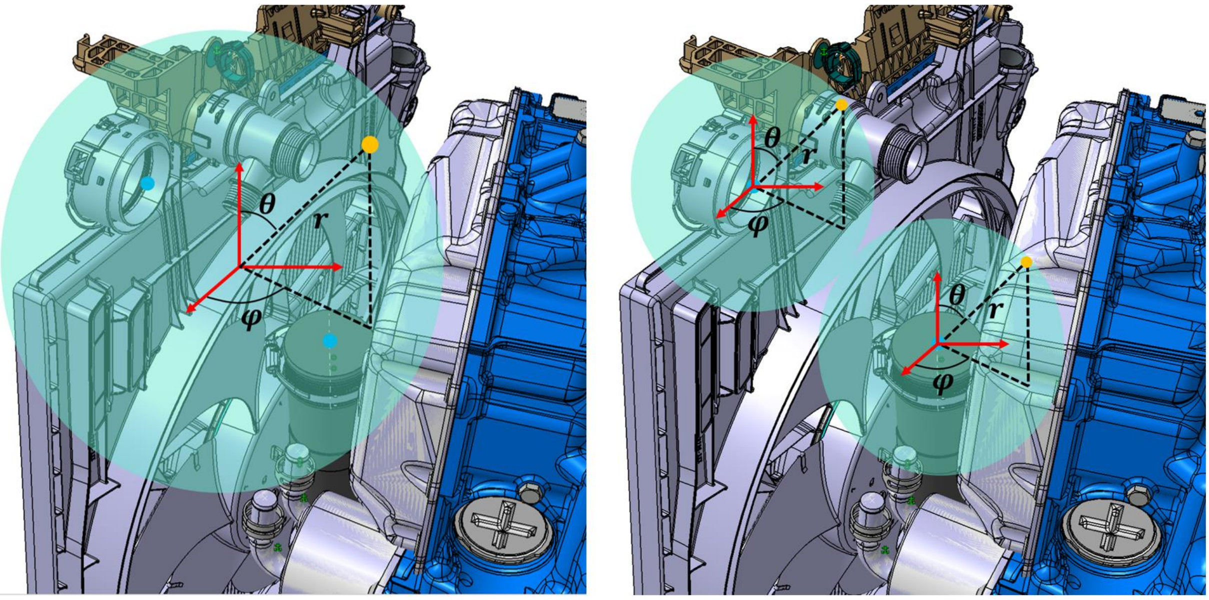

Figure 4. Definition of the spheres where the via-points can be placed; one via-point to the left and two via-points to the right. The placement of each via-point depends on three variables for each point (r, θ, φ)

4. Implementation and test

The proposed method has been implemented using CATIA, Excel and Industrial Path Solutions (IPS); CATIA as the CAD software, Excel for the interface and IPS as simulation software. In the Excel-interface the coordinates of the nodes are extracted from the CATIA-model through Visual Basic (VBA). With VBA, a Lua script (Lua, 2019) is created with the information from the Excel sheet containing setup values for the hoses that are to be routed; coordinates for start- and end-nodes and

via-points, routing order and cross-section dimensions of the hoses. The script contains IPS functions for generating the routing automatically by utilizing their built-in path planning algorithms and simulations for calculating stresses as well as measurements of the hose segments in terms of lengths and clearance.
To test this implementation, an industrial case from a car manufacturer have been used, where three hoses with two different cross-section dimensions are routed within the same space. The original hoses were removed from the original CAD-geometry and one of the remaining components was chosen as a critical component with need of extra clearance. No clearance constraint was set to the other surrounding geometry in the test case, except for (the build-in) requirements on collision free paths for the hoses. Two optimizations were run; one where one via-point per hose was optimized and the other where two via-points were optimized. Both were run using the genetic algorithm MOGA-II. For the case with one via-point per hose the genetic algorithm was set to 30 individuals through 60 generations and for the case with two via-points per hose to 40 individuals through 200 generations. In both cases, the first generations were generated using Uniform Latin Hypercube sampling and with ModeFRONTIER as the optimization engine. The total optimization time was approximately 16 and 80 hours, respectively on a desktop computer (Intel Xeon CPU E3-1245 v6 @ 3.70 GHz, 16 GB RAM). The results are presented in Table 1, containing a couple of pareto optimal solutions from each optimization run, compared with the reference solution. Figure 5 shows an optimized assembly (with one via point per hose) generated from the framework together with the original reference solution.

Table 1. Results from test case

	Total material volume $[dm^3]$	Maximum stress $[MPa]$	Clearance to component $[mm]$	Clearance between hoses $[mm]$
Reference solution	0.322495	-	8.981	14.63
Optimized solution with one via-point, I	0.386862	3.0003941	9.846	25.983
Optimized solution with one via-point, II	0.340716	5.0685105	8.817	10.006
Optimized solution with two via-points, I	0.316168	3.3817365	9.913	9.633
Optimized solution with two via-points, II	0.335602	3.3148586	10.112	21.047

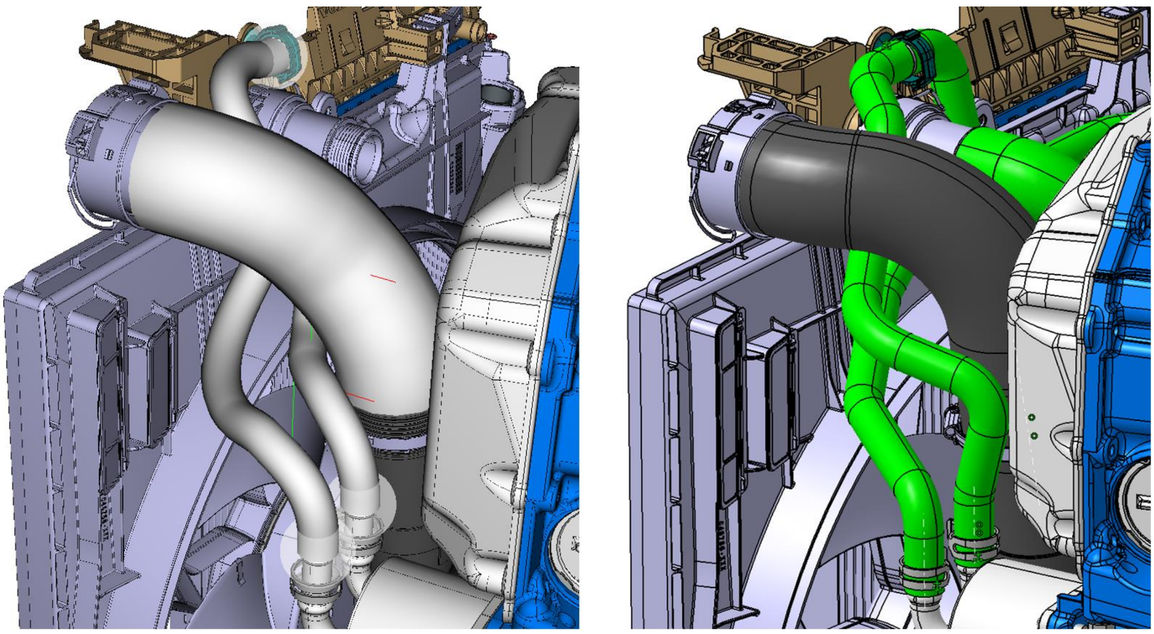

Figure 5. Optimized assembly to the left and the original solution to the right

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Figure 6 shows and excerpt from the interface created in Excel for the implementation of the proposed method. Three buttons were created which enable user initiation of CAD-data extraction, automatic hose routing in IPS and extraction of results. The “Routing Input” cells in the interface contain information about the three hoses that are routed, and in this example the permutation of the hose routing order is 2-1-3, meaning that hose B will be routed first, followed by A and last C. The “IPS data” cells contain the measured routing data that are summed together in the “Routing Results” cells which are used as the objective function values used in the optimization.

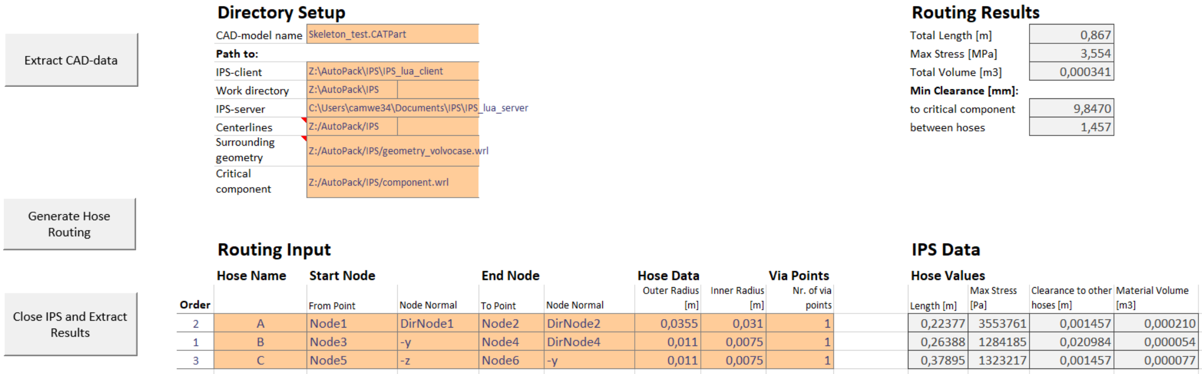

Figure 6. Excerpt from the interface in Excel

5. Discussion

The proposed method and belonging framework is capable of generating a set of pareto optimal solutions of hose routing assemblies. The framework automates repetitive steps of the hose routing development process, and generates assemblies that can be adjusted on detail level by the engineers and by that save time in the development process and enable exploration of the design space in an effective manner.

What is included in the framework is limited by a few things. For one, it is limited by the functionality of the simulation software, secondly by computational cost and thirdly by what is possible to quantify. There is a trade-off between computational cost for the optimization and number of characteristics to evaluate. Adding more variables, objectives and simulations could generate a hose assembly closer to the final solution but would mean higher computational cost for the optimization to converge and find acceptable solutions as the optimization problem would get more complex and the additional simulations would extend the time for each evaluation. One time consuming simulation that has not been included in this implementation of the proposed method is dynamic simulations which can show dynamic clearance and stress. In a dynamic simulation, the engine is allowed to move (to shake and rattle as during driving), and the corresponding dynamic stresses and movements of the hoses are kept under control. Instead of using a dynamic simulation which gives a more correct dynamic clearance, static clearance objectives are used to compensate for that. If adopted in industry, dynamic simulations could be performed after the optimization manually by the engineers. Hence, in the detailed design stage the engineers can select a set of pareto optimal assembly designs and conduct dynamic simulations to gain more information for assessing which design to take further and which parts of that design that needs adjustment.

Other evaluations that is not included and is harder to quantify is the ergonomic aspects of human assembly which has been pointed out as a future work in the area of computational methods for geometrical design (Hermansson, 2017). In cases with higher number of hoses to include in the optimization causes a combinatorial explosion when deciding the order in which the hoses could be routed in. Since the optimization framework in the proposed framework generates a set of pareto optimal solutions, the engineers can make the overall assessment of the solutions and choose and modify the solutions with respect to the aspects that have been left out of the optimization framework.

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Apart from this, modifications in the optimization setup could also be done. In this implementation, the via-points were placed within restricted areas in shapes of spheres, but could be defined differently to gain other optimization results. The number of via-points could also be varied and used as a variable in the optimization, that is, let the optimization decide not only the placement of the via-points but also number of via-points used for each hose. A way to more efficiently conduct the optimization would be to implement smarter method to handle designs where the via-points lead to intersections with the surrounding geometry. In the method presently used, collisions are detected in the routing simulation environment, which is a time-consuming simulation. Instead of letting the simulation software attempt to find a collision free path where a collision is in fact inevitable, those designs could be discarded earlier. To perform a clash analysis in the CAD environment for each iteration in the optimization would add unnecessary time to the optimization in the cases where there is no intersection of the via-points, and would therefore not speed up the overall process. Instead, the design space should be reduced to only include feasible via-points, possibly at the cost of a longer time to setup the problem. This is considered as a future work in the development of the proposed method and optimization framework. Further future work could be to test the framework in other cases to evaluate and develop the method and calibrate the framework further.

All in all, with the increased complexity that comes with new systems that are being introduced in modern vehicles, the development process could benefit from the proposed method in this paper. The proposed method provides a tool to increase the integrated knowledge in the development process, and has been implemented in a test case showing promising results and that enables integration with the existing CAD systems providing ease of deployment.

6. Conclusions

In this paper, a proposed method for automation and optimization of routing of multiple hoses in the engine compartment of vehicles is presented. A framework has been developed and implemented using CATIA, Excel and IPS, and it has been tested on an industrial case from a car developer. The framework provides exploration of design space options in the early stages of the design process, where the design freedom is at its highest. The framework enables unbiased evaluation of multiple objectives at once, providing a conceptual assembly of the hoses which then can be adjusted by the engineers. If deployed in industry, the proposed method has the potential to reduce the numbers of iterations needed in the development process and aid the development of better products in an efficient and effective way. The framework and proposed method is generic and modular and can thus be reused in several and continuous development cases as well as other applications than vehicles without major modifications.

Acknowledgments

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