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# Integrated equipment installation and optimisation for new engine architecture nacelles

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# Integrated equipment installation and optimisation for new engine architecture nacelles

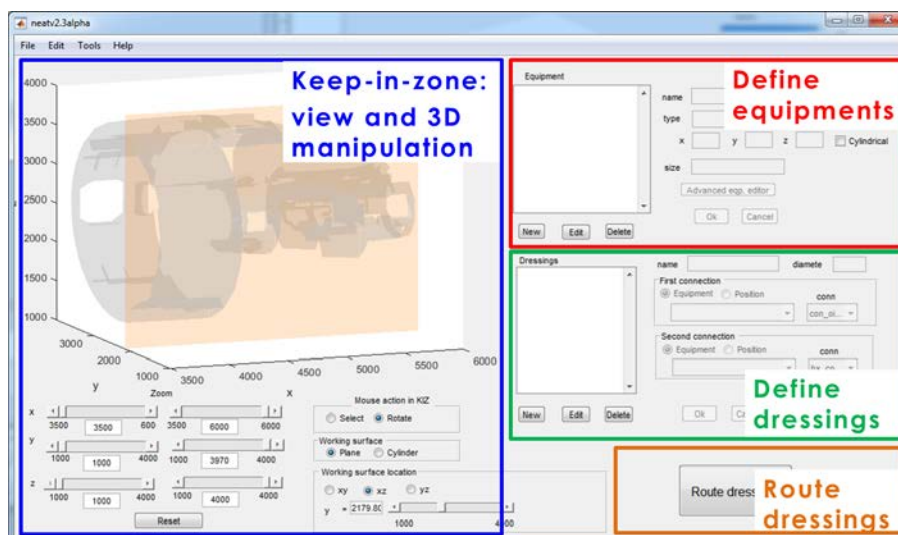


Figure: Main window of the software tool NEAT.

## Problem area

With the development of new turbofan aero engines, such as the Ultra-High Bypass Ratio (UHBR) engine and open-rotor solutions, advances in propulsion and fuel-efficiency can be made through increasing fan diameters and higher bypass-ratios. Several enhancements to the overarching integrated power plant system (IPPS) design are needed, in particular a shorter and slimmer nacelle. This will provide less space for the engine systems installation and for ventilation solutions. Moreover, higher operating temperatures and accessibility for maintenance further complicate the feasible arrangement of all the required engine equipment.

## Description of work

To address these challenges, better ways of developing integration solutions for the IPPS are required. Optimisation methodologies and toolsets that allow the

### REPORT NUMBER

NLR-TP-2017-297

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### REPORT CLASSIFICATION

UNCLASSIFIED

### DATE

December 2017

### KNOWLEDGE AREA(S)

Aerospace Collaborative Engineering and Design

### DESCRIPTOR(S)

UHBR

aircraft turbofan

routing

harnesses

keep-in-zone

complete system to be developed and trade studies to be assessed are being investigated in the EU H2020 research project NIPSE. This optimisation approach considers the placement of equipment as well as the routing of ducts and harnesses between these equipment. In particular, the optimisation approach is built on a graph based approach involving efficient routing algorithms that rely on variants of the well-known Dijkstra's algorithm. This approach not only provides a potentially better answer than current methodologies used in industry, but the automation aspect provides solutions faster allowing the development time of the IPPS to be reduced. This development is achieved by applying different optimisation methodologies to key variables in order to identify the best overall methodologies to achieve the best solution in the shortest time.

## Results and conclusions

This paper presents design and optimisation methodologies that are developed for the integrated equipment installation into the restricted volume of new architecture aero engines' nacelles. The focus in this paper is on highly efficient and flexible placement of equipment and automated routing of pipes, ducts and harnesses. The implementation of the methodology aims for easy user interaction, allowing design engineers to quickly make changes to equipment installations taking into account the relevant installation rules for example for clearances, accessibility and temperature constraints.

## Applicability

Besides the methodology, also the software implementation is presented, in particular the software tool NEAT (Next generation engine Equipment Allocation Tool) and its application to aero engine equipment installation design cases. The methodology is very flexible and well-suited for other industrial applications like aircraft harnesses routing and design.

### GENERAL NOTE

This report is based on a presentation held at the EUCASS 2017 conference, Milan, Italy, 3-6 July 2017.

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<b>OWNER</b>	NLR
<b>DIVISION NLR</b>	Aerospace Vehicles
<b>DISTRIBUTION</b>	Unlimited
<b>CLASSIFICATION OF TITLE</b>	UNCLASSIFIED

APPROVED BY :																				
AUTHOR					REVIEWER					MANAGING DEPARTMENT										
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## Summary

The development of new higher efficiency turbofan aero engines requires several design enhancements that typically result in shorter and slimmer nacelles. Consequently these engines provide less space for the engine systems installation and for maintenance accessibility. In the NIPSE project, optimisation methodologies are being investigated and developed for the integrated installation of equipment into the restricted volume of new architecture engines' nacelles. The underlying optimisation methodology is built on a graph based approach involving efficient routing algorithms. Besides the methodology, also the software implementation and its application to engine equipment installation design cases are presented in this paper.

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# Integrated equipment installation and optimisation for new engine architecture nacelles

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## Abstract

The development of new higher efficiency turbofan aero engines requires several design enhancements that typically result in shorter and slimmer nacelles. Consequently these engines provide less space for the engine systems installation and for maintenance accessibility. In the NIPSE project, optimisation methodologies are being investigated and developed for the integrated installation of equipment into the restricted volume of new architecture engines' nacelles. The underlying optimisation methodology is built on a graph based approach involving efficient routing algorithms. Besides the methodology, also the software implementation and its application to engine equipment installation design cases are presented in this paper.

## 1. Introduction

With the development of new turbofan aero engines, such as the Ultra-High Bypass Ratio (UHBR) engine and open-rotor solutions, advances in propulsion and fuel-efficiency can be made through increasing fan diameters and higher engines' bypass-ratios [1]. For this, further examination of the integration of the engine into the aircraft is needed. Several enhancements to the overarching integrated power plant system (IPPS) design are needed to achieve the envisaged higher efficiency of these engine architectures, in particular a shorter and slimmer nacelle. This will provide less space for the engine systems installation and for ventilation solutions. Moreover, higher operating temperatures and accessibility for maintenance further complicate the feasible arrangement of all the required engine equipment.

To address these challenges, better ways of developing integration solutions for the IPPS are required. Optimisation methodologies and toolsets that allow the complete system to be developed and trade studies to be assessed are being investigated in the EU H2020 research project NIPSE [2]. These methodologies and toolsets consider the IPPS to be optimised as a whole, with best solutions for weight and drag easily identified very quickly during the development process. This optimisation approach considers the placement of equipment as well as the routing of ducts and harnesses between these equipment. This not only provides a potentially better answer than current methodologies used in industry, but the automation aspect provides solutions faster allowing the development time of the IPPS to be reduced. This development is achieved by applying different optimisation methodologies to key variables in order to identify the best overall methodologies to achieve the best solution in the shortest time.

Optimisation algorithms for routing problems have been extensively investigated in the past, e.g. for optimum route planning in transportation problems. So called graph algorithms have proven very successful for that. Early developments are for example the well-known Dijkstra's algorithm [3] and the A\* algorithm [4] and many subsequent variants and implementations thereof [5], all of which address the basic problem of the calculation of the shortest path in a graph of interconnected nodes between two given points, assigned as source node and destination node. More specifically, graph based approaches for system installation problems have also been investigated. For example [6] presents the investigation of machine-executed compilation of graph-based design languages to efficiently address topological and parametrical design problems, with application to aircraft cabin system design. Typically, for example in harnesses or pipework routing, important criteria for the routed path are not only total path length, but also other cost factors that may depend on local conditions in the routing space, like installation aspects (clamps, insulation, thermal protection etc.) and segment bend radius of local curvature, as has been investigated for example in [7].

The present paper describes the design and optimisation methodology that is developed for the integrated equipment installation into the restricted volume of new architecture aero engines' nacelles. The focus in this paper is on highly efficient and flexible placement of equipment and automated routing of pipes, ducts and harnesses. The implementation of the methodology aims for easy user interaction, allowing design engineers to quickly make changes to equipment installations taking into account the relevant installation rules for example for clearances, accessibility and temperature constraints. This optimisation methodology is built on a graph based approach involving efficient routing algorithms that rely on variants of Dijkstra's algorithm. Besides the methodology, also the software implementation is presented, in particular the software tool NEAT (Next generation engine Equipment Allocation Tool) and its application to aero engine equipment installation design cases.

## 2. The challenge in the nacelle

New turbofan aero engines, like the UHBR engine, require smaller and thinner nacelles. As a result, the engine equipment shall be installed in more confined space with higher operating temperatures. An indicative illustration of this spatial reduction of a UHBR nacelle in comparison with a proportionally scaled current state-of-the-art nacelle is given by the red (scaled current) and green (UHBR) areas in the figure 1 below.

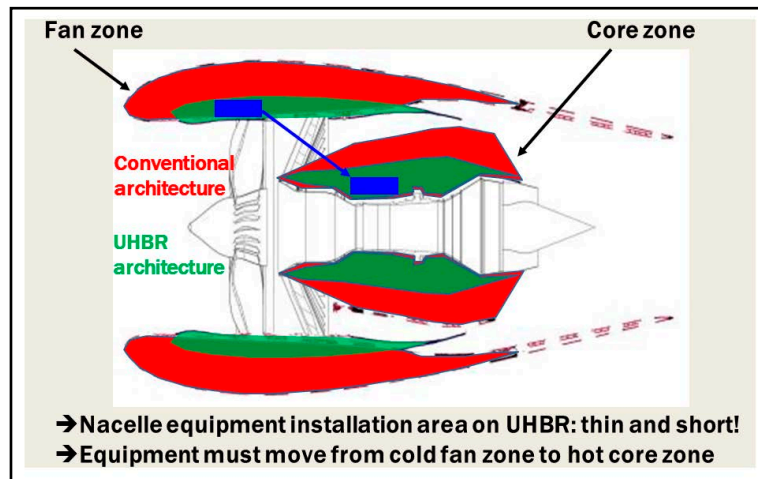


Figure 1: Illustration of the smaller and thinner nacelles typically required for UHBR engines.

This confined space, identified here as the keep-in-zone (KIZ) for the engine equipment, globally comprises some interconnected compartments: mainly the fan zone, the bifurcation zone and the core zone, as illustrated in figure 2.

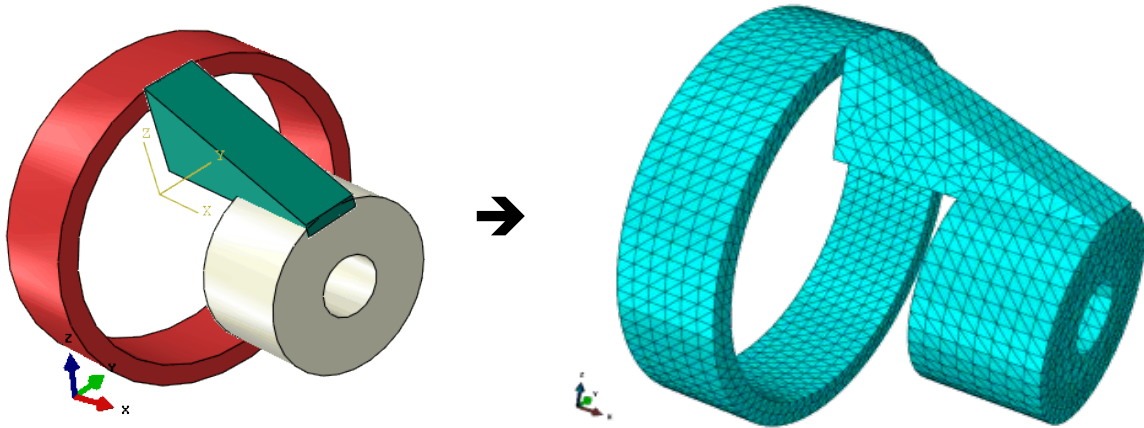


Figure 2: Illustration of the interconnected compartments (fan zone in red, bifurcation in green, core zone in grey) in the simplified KIZ as defined in a 3D CAD model (left), and its discretised representation by unstructured triangulated surfaces (right).

This KIZ is typically defined in three dimensional (3D) computer aided design (CAD) models by aero engine OEMs (original equipment manufacturers) and nacelle manufacturers. To translate such 3D CAD models of the KIZ into models that can be used for installation and routing optimisation, these CAD models can be simplified and discretised typically into unstructured triangulated surface representation as for example in STL (stereo-lithography) file format. Such STL file then contains the (approximate) representation of the outer surface of the complete KIZ's 3D geometry. The STL surface representation can be used to create a graph that represents a large set of small 3D cells (of cubic or other hexahedral shape, or potentially cells with other shapes like tetrahedral or pentahedral might be used) that approximately fill the complete volume of the KIZ. Such a KIZ-graph can for example be achieved with a set of cube-shaped cells defined in a Cartesian grid, as illustrated in figure 3.

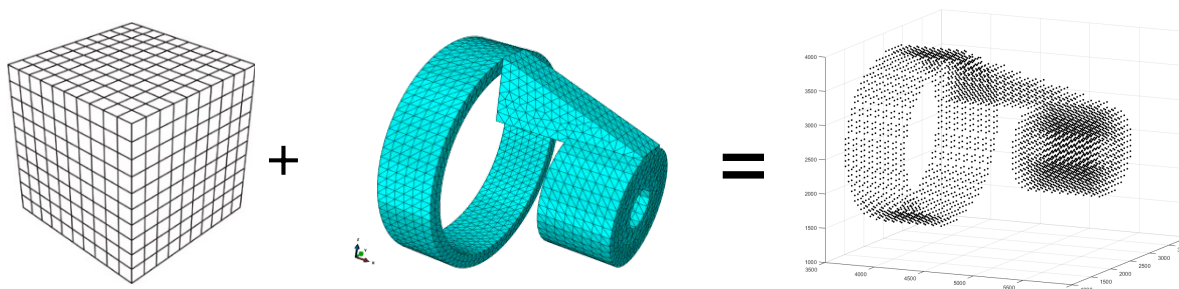


Figure 3: Illustration of the creation of a KIZ-graph, in this case based on a very coarse grid of cells. The KIZ-graph is created based on a set of cubes defined in a Cartesian grid (left). From this grid, the cubes are selected that are inside the KIZ triangulated surface (middle). These selected cubes are then used for the KIZ-graph, i.e. these graph-nodes represent the centres of the selected cubes (the black dots in the picture on the right).

It should be noted that the graph essentially represents only the set of indexed nodes, e.g. representing the centres of the 3D cells inside the KIZ, and the desired connections between the nodes, e.g. for each node the connection to each of its neighbouring nodes. Thus the nodes can be linked to 3D coordinates that represent locations in the KIZ, and the node-connections can be linked to the 3D Euclidian distances between the connected nodes. This allows for a highly efficient data structure on which graph based routing algorithms can be applied for highly efficient calculations of shortest path between arbitrary pairs of nodes. Typically the core data structure requires only  $(n_{c,i} + 1)$  integers per

node, where  $n_{c,i}$  is the number of connections of node  $i$ , and one real number  $l_j$  per connection representing the length of connection  $j$ .

All sorts of manipulations can be performed on the graph, for example the exclusion of a node from the graph once this node has been assigned to a routed path, and as such represents an obstacle for subsequently routed paths. Similarly nodes can be excluded from the graph if they are assigned to an equipment, i.e. if an equipment (for example an electric component box) is defined in a certain location in the KIZ. Of course many other types of manipulations of the graph and its further processing are possible, for example by applying “weights” or “penalty factors” to certain preferred or disfavoured node connections due to certain routing directions or temperature conditions in the KIZ.

Various settings for the creation of the graph can be defined. Important choices are for example whether a 3D Cartesian or cylindrical grid of cells is used to create the graph. For the considered aero-engine KIZ, which is more or less cylindrical, a cylindrical grid of cells is more efficient for conformal mapping of the grid cells to the KIZ surface. Also, obviously, the cell size of the grid is important for the accuracy of the mapping of the grid cells to the KIZ geometry, see figure 4.

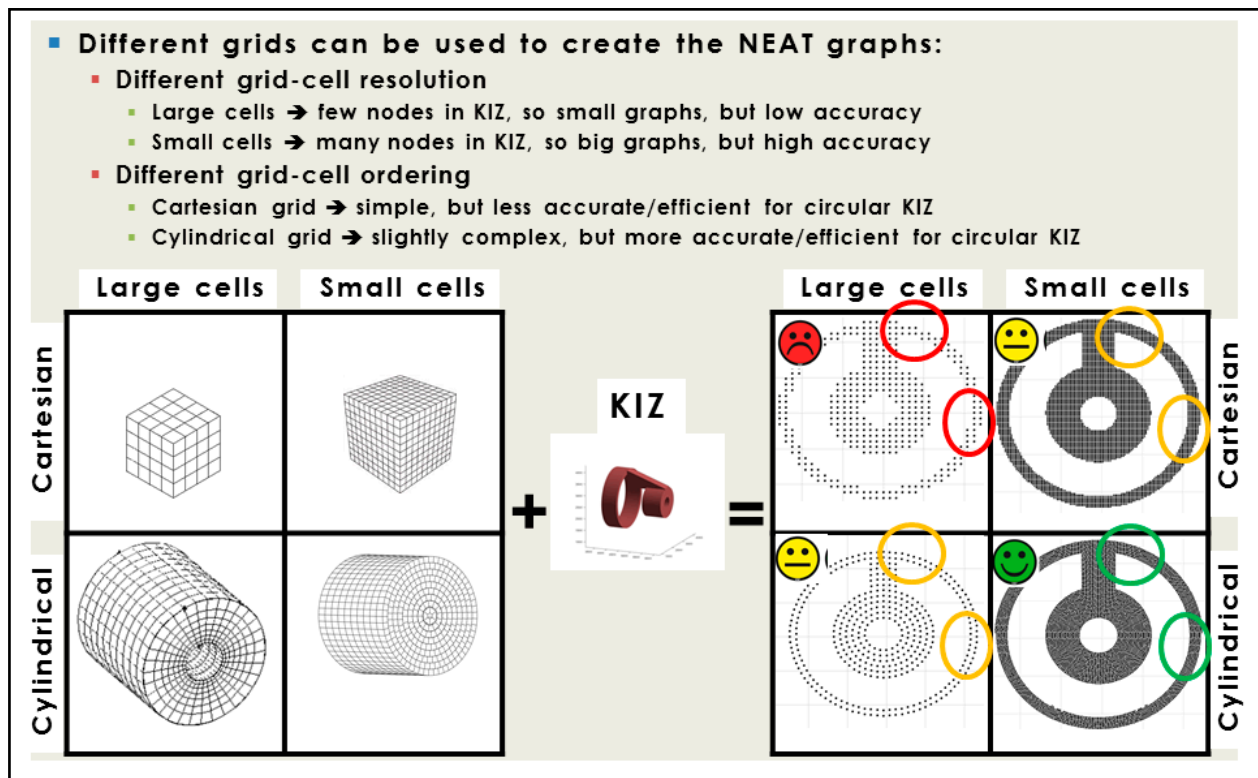


Figure 4: Illustration of the effects of different choices for the grid shape and grid cell size on the accuracy of the created KIZ-graph.

The grid cell size is also important for the representation of the size of the routed components. Typically the routing can be most efficiently performed if these sizes are more or less equal. For example, the routing of a harness with a 10 mm diameter is most efficiently achieved if a 10 mm grid cell size is used. Hence, several graphs based on different grid cell sizes are applied for the routing of differently sized components.

### 3. Equipment placement and routing in the graph

With the KIZ-graph available, equipments can be easily inserted in the graph. Equipments exclude from the graph certain groups of nodes that are located in the KIZ space that is occupied by the equipment. Equipments typically have several connector-nodes, i.e. nodes to which pipes, ducts or harnesses can be connected. The pipes, ducts or harnesses will be further referred to as “dressings”. As such, connections between equipments can be defined. Also

connections between equipments and/or arbitrary locations in the KIZ (e.g. harness connectors at the KIZ surface) can be made, as is illustrated in figure 5. With the graph algorithms, optimised routings of dressings can be very efficiently determined from the KIZ-graph and various constraints or penalties can be incorporated in these routing optimisations. The resulting routed dressing as such occupies the KIZ space of the grid cells that correspond to the sequence of graph nodes that were determined for the dressing's route. Therefore the grid cell size (typically: cube edge length) should more or less correspond to the size (typically: the diameter) of the dressing that is routed, and consequently dressings of different sizes require graphs that are based on grid cells of different sizes.

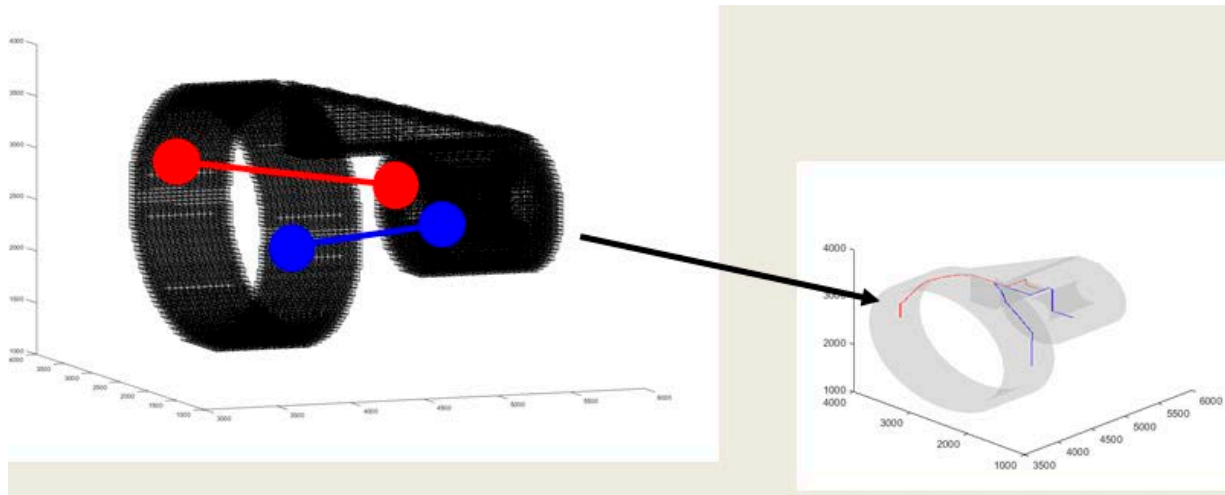


Figure 5: Basic illustration of the creation of 2 connections (indicated in the left picture by red and blue in the large set of black KIZ nodes). Each connection is defined between 2 connectors in the fan- and core-zones, and the resulting optimum routed dressings (also in red and blue in the right picture) are calculated within the KIZ (KIZ is indicated by the grey shaded surfaces in the right picture).

#### 4. Aero-engine equipment, connectors and dressings

The aero-engine equipments considered in this study are of various types, like electric equipment, hydraulic equipment or pneumatic equipment. Some examples are electric components (e.g. electric generators), electronic boxes (e.g. for control units), oil coolers (e.g. for air-oil heat exchangers), or air valves (e.g. for bleed air systems). Typically these equipments are interconnected in different ways. For example an electric generator may be connected by electric harnesses to electronic power consumers and to electronic control units and by oil pipes to a heat exchanger. For these interconnections, or dressings, the equipment has several connectors that are located somewhere on the outer surface of the equipment.

In the design phase of an engine, the locations of these connectors on an equipment may be not fully fixed, but yet to be determined in combination with the placement and orientation of the equipment in the engine installation. Therefore it is important in engine installation studies to have flexibility in the definition of the locations of these connectors. Normally these equipments are designed and defined in CAD software, in which highly detailed definitions of geometry and properties can be created. These details are less important in engine installation studies, in which slightly simplified geometric definitions of geometry and connectors may be sufficient. Nevertheless, for easy adoption of the equipment information as readily available from its CAD model, the automated translation of this CAD model to the equipment's simplified geometric representation, for example by surface triangulation stored in an STL file, is an efficient way for incorporating equipments in engine installation studies. As an example, a basic solid CAD model of an electric generator is given in figure 6, together with its simplified surface triangulated geometric representation and its connectors' locations.

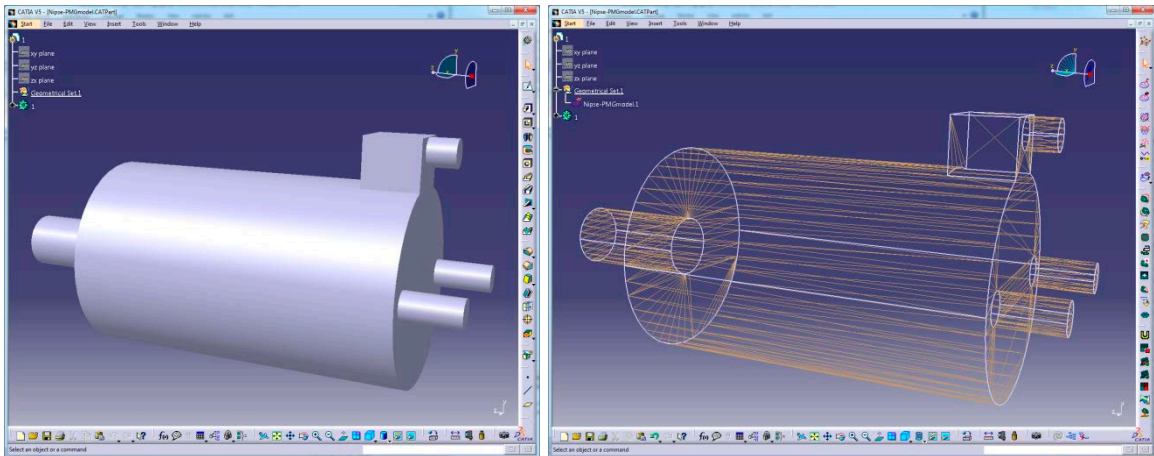


Figure 6: Basic illustration of a solid CAD model (left) of an electric generator. The simplified surface triangulated geometric representation (right) of this electric generator can be automatically generated in common CAD software like Catia [8]. Connector locations are included in this CAD model as the small cylindrical parts on the right, representing the electric connector location (on the top-right) and the hydraulic (oil-in and oil-out) connector locations (on the lower-right).

## 5. Graph-based routing

In engine installation studies, various possible locations of the equipments in the KIZ and of the connectors on the equipments should be easily defined and the feasibility of the required dressings (i.e. interconnections) and their optimal pathways (i.e. routes) should be quickly determined. This can be achieved with the use of the KIZ graph and the equipments' STL files. For example, electric generators and oil cooler heat exchanger equipments can be easily positioned in the 3D KIZ volume and the KIZ graph can be updated correspondingly, i.e. accounting for the space occupation of these equipments and the locations of their connectors. This is illustrated in figure 7.

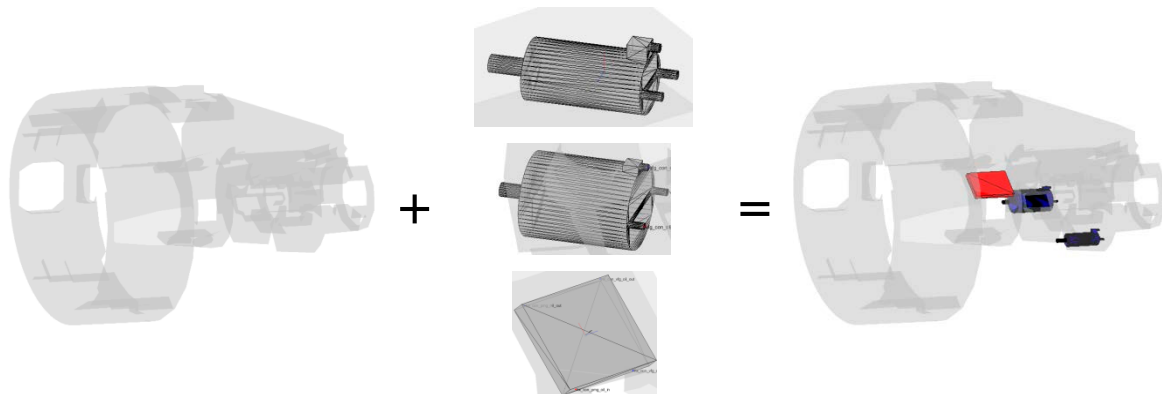


Figure 7: Basic illustration of the 3D KIZ volume (left) and the triangulated geometries of 2 electric generators and 1 oil cooler heat exchanger equipments (middle), and their positioning in the 3D KIZ volume (right).

Appropriate connections between these equipments can then be easily defined, simply by relating the desired connectors to each other, for example for an oil pipe between the oil connectors of the generator and the heat exchanger, as illustrated in figure 8.



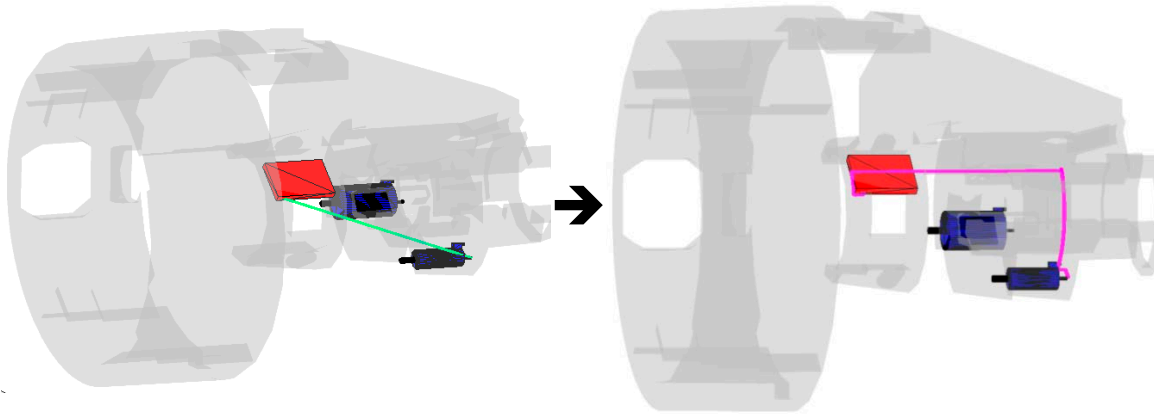


Figure 8: Illustration of the definition of a connection (left picture) for an oil pipe between the oil connectors of the generator (blue cylinder) and the heat exchanger (red box). Also the resulting actual oil pipe of 20mm diameter routed through the KIZ is shown (right picture).

The routing algorithm can then be applied to automatically determine the optimal route for the oil pipe properly through the KIZ and avoiding the occupied space of other equipments or already existing dressings.

## 6. Software tool development

The optimisation methodology that is built on the graph based approach has been implemented in a software tool. The implementation of this software tool aims for easy user interaction, allowing design engineers to quickly and intuitively make changes to equipment installations taking into account the relevant installation rules. An implementation of this software tool has been developed in Matlab-R2015b [9]. Matlab provides a good basis for efficient data structures and for graph manipulation and optimisation algorithms. Also the development of interactive graphical user interfaces (GUIs), of functionality for 3D results visualisation and of stand-alone (i.e. outside the Matlab environment) executable programs are well supported. The resulting software tool (NEAT - Next generation engine Equipment Allocation Tool; see figure 9) is operational in Microsoft Windows [10] environments (Windows 7, Windows 10) and can be easily ported to Matlab-supported environments.

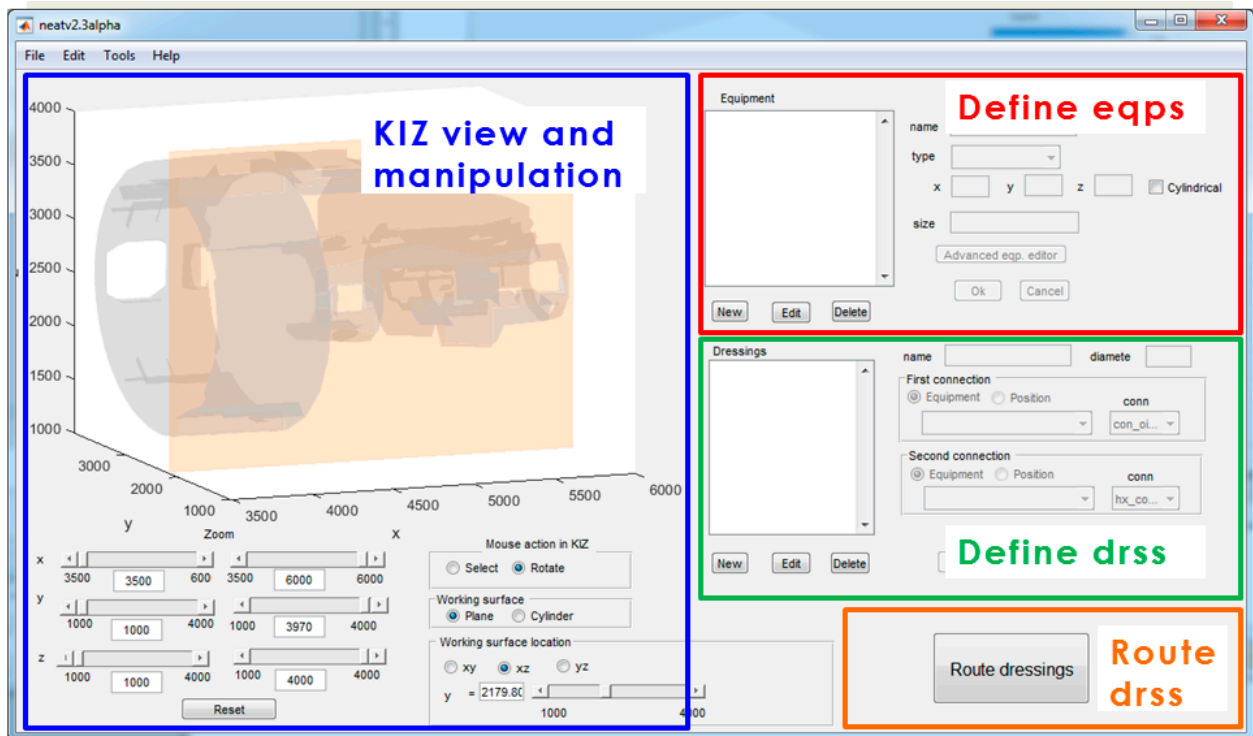


Figure 9: Main window of the software tool NEAT.

The NEAT tool provides an interactive visual representation of the KIZ (on the left side in figure 9) that allows for view manipulations like zooming, 3D rotation and point-and-click coordinate selection. The NEAT tool is based on the KIZ of a UHBR engine, but it should be noted that this KIZ can relatively easily be replaced by a KIZ of another engine (or even of a quite different system, for example of an aircraft fuselage or a satellite). NEAT also provides functions (on the right side in figure 9) to define, locate and orientate equipments and to define and route dressings in the KIZ. Configurations can be created and are defined in terms of equipments and connections in the KIZ. These configurations can be saved to and read from Excel files. If the dressings, as defined by the connections and routed by the graph algorithms, have been generated, then the resulting installation can be saved to (or read from) specifically formatted binary data file (based on Matlab's mat-file [9] format). The NEAT tool also provides various other types of settings and manipulations for the positioning and routing of equipments and dressings, such as applying "weights" or "penalty factors" in certain areas of the KIZ graph to define preferred or dis-favoured routing directions or by applying lower limits to the allowed bending radius of routed dressings. The complete functionality of the tool cannot be fully explained in this paper, but in the next section the main functionality will be demonstrated.

## 7. Application case studies

We will consider a relatively simple case study, in which the installation of some electric and hydraulic equipments in the KIZ is investigated. First, an electric generator equipment that has been defined in a Catia CAD model, as was previously shown in figure 6, is imported into NEAT and positioned in the desired location and orientation in the core zone part of the KIZ. Also some connectors are defined on the electric generator, which are used for connecting the electric harnesses and the oil pipes for cooling. Illustration of this generator equipment definition in NEAT is given in figure 10.

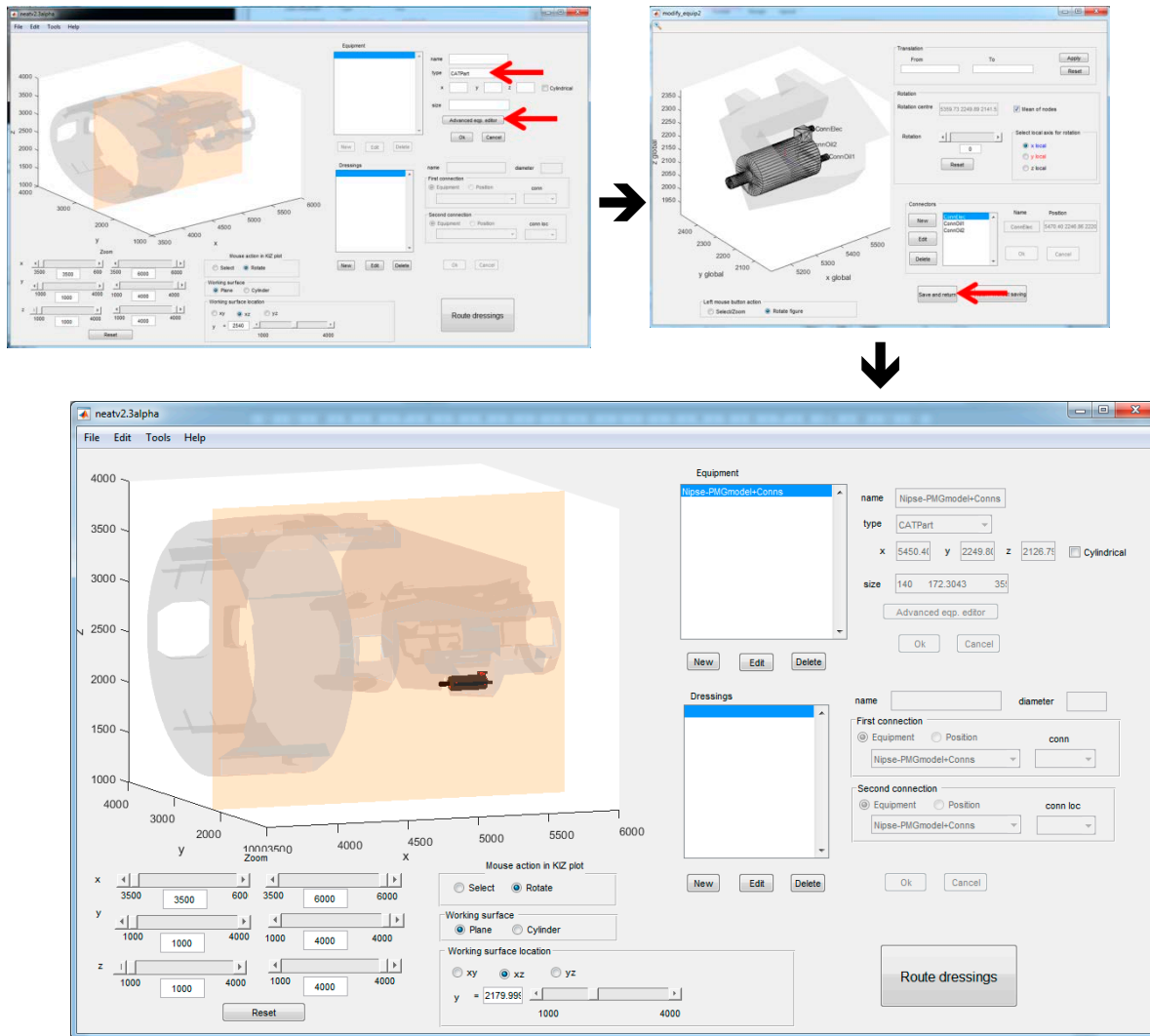


Figure 10: Illustration of the generator equipment definition in NEAT, where the equipment geometry is imported from a CAD model (upper left picture), moved into the correct location/orientation and devised with electric and oil connectors (upper right picture) and then saved in the KIZ (lower picture).

Subsequently, another slightly different electric generator equipment is imported into NEAT, is devised with electric and oil connectors, and is positioned in the core zone part of the KIZ. Then a heat exchanger equipment is defined in NEAT, as is illustrated in figure 11. This heat exchanger equipment is not imported from a CAD model but directly defined in NEAT as a flat box shape, which is a strongly simplified representation of its approximate geometry. Also 4 oil connectors are defined on the heat exchanger (for connections with both the generators).

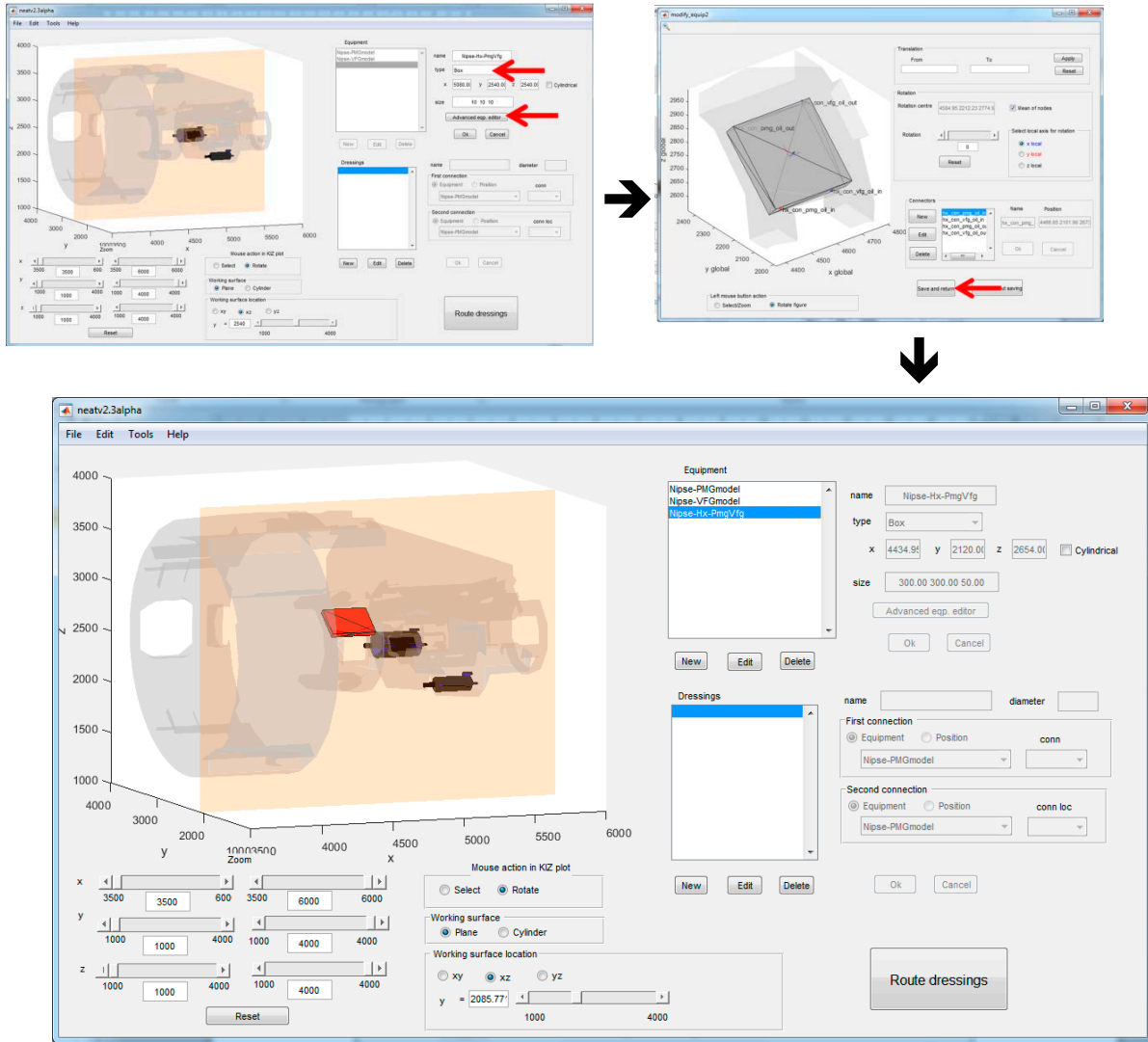


Figure 11: Illustration of the heat exchanger equipment definition in NEAT (upper left picture), where the equipment geometry is directly created in NEAT and moved into the correct location/orientation and devised with oil connectors (upper right picture) and then saved in the KIZ (lower picture).

After the equipments have been defined and positioned correctly in the KIZ, dressings can be easily defined by creating connections between equipment connectors. For example an oil pipe dressing between the first generator and the heat exchanger can be defined, as shown in figure 12.

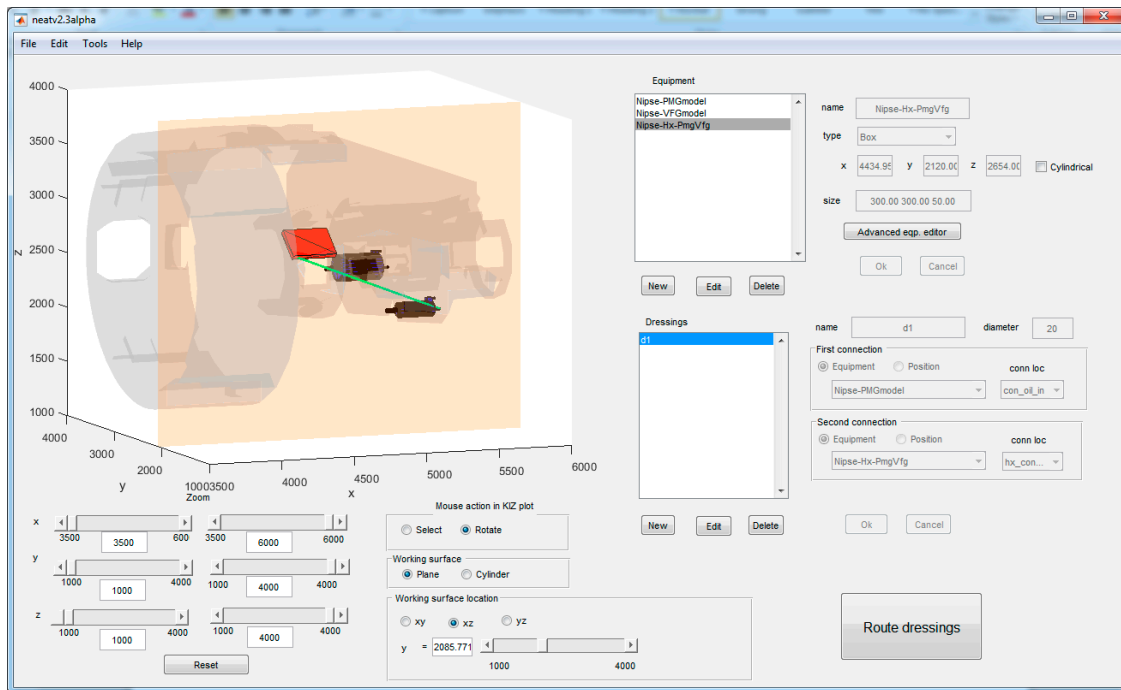


Figure 12: Illustration of the definition of an oil pipe dressing between the first generator and the heat exchanger, which can be easily defined by creating connections between the equipment connectors (indicated by the green line in the 3D view on the upper left).

The resulting configuration data, containing all the relevant data of the equipments and dressings (like their name, shape, filename, position, size, type, connectors, etc.), can be directly exported from NEAT to Excel [11]. The resulting configuration Excel file (as is shown in figure 13) can also be manipulated (i.e. equipments and dressings can be changed or added) and imported back into NEAT. This allows for easy creation, editing and exchange of NEAT configuration models outside the NEAT tool.

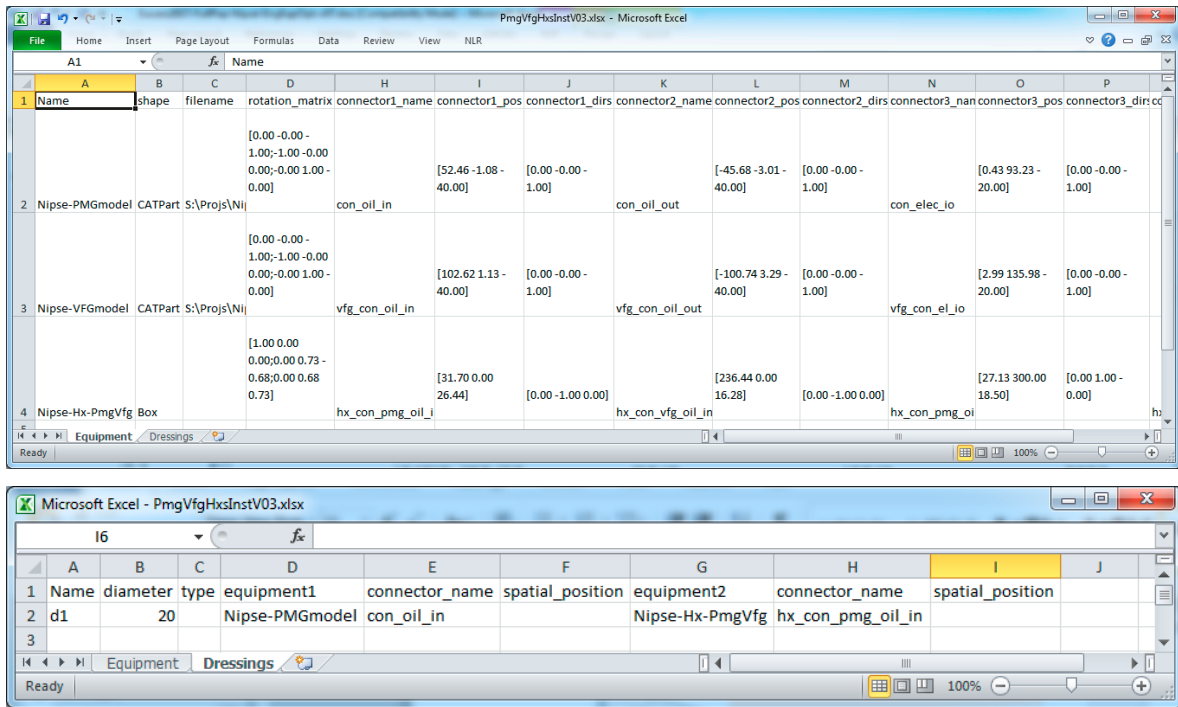


Figure 13: Illustration of the configuration Excel file containing the definitions of the 2 generator equipments and the oil pipe dressing as shown in figure 12.

It should be noted that the configuration Excel file does not contain the information of the routed dressings, but only the dressing definitions (like name, connectors, diameter etc) that are needed by the routing algorithm to determine the routing of a dressing. For example the oil pipe dressing that was defined can be easily routed through the KIZ (by the button “Route dressings”), yielding the routed dressing as was shown above in figure 8 (right picture). Similarly the other dressings between the equipments can be defined and their routes can be determined. Subsequently the routes for the oil dressings for both the generators from and to the heat exchanger are determined, as well as the routes for the electric dressings for both the generators to the so-called junction box (i.e. a surface on the KIZ in the bifurcation zone where the systems interface between the engine and the aircraft is located). The resulting installation of the 3 equipments and the 6 routed dressings is shown in figure 14. For the further processing of these preliminary design results of the installed equipments and the routed dressings, it is necessary to analyse these results in more detail. Therefore the resulting installation can be directly exported to a Catia CAD model (as is also shown in figure 14) allowing an engine OEM to incorporate the installation in their more detailed engine and nacelle design processes.

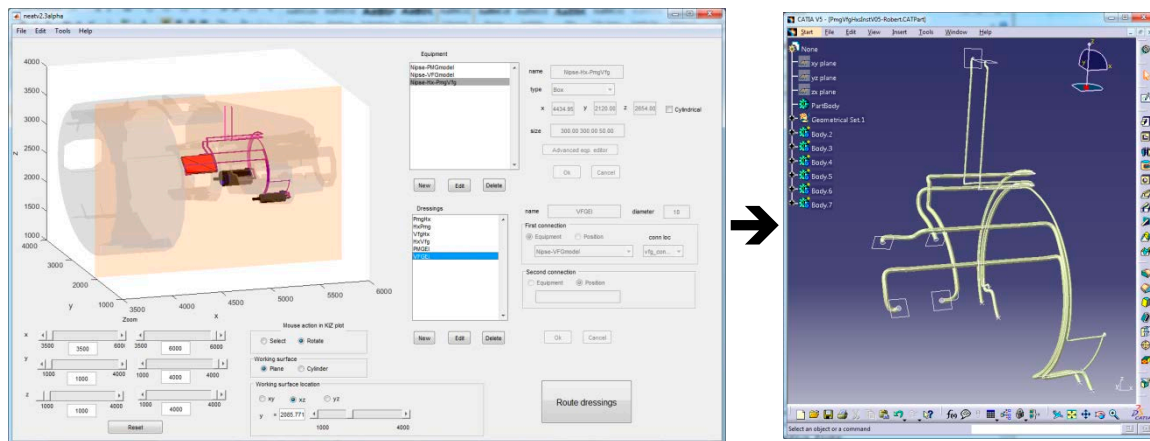


Figure 14: Illustration of the resulting installation of the 3 equipments and the 6 routed dressings in NEAT (left picture) and the routed dressings exported to a Catia CAD model (right picture).

It should be noted that the installed equipments and the routed dressings as shown in this use case are simplified examples, not intended to represent a real engine equipment installation but merely to demonstrate the possibilities for preliminary design and routing of such equipment installations. Installations with higher numbers of more realistic components and with more complex installation rules are being considered in further ongoing investigations.

## 8. Results

The preliminary design process with the NEAT tool that was followed in this use case for the user-interactive installation of equipments and automated routing of dressings could be performed in limited amount of time. The interactive import of the generator equipments from already available CAD parts and their proper positioning in the KIZ, and the interactive creation and positioning of the simplified (box) equipment for the heat exchanger required less than 1 man-hour of work. The automated routing of the 6 dressings required less than 1 minute computation time on a standard PC (Intel Core i5-3320M CPU@2.6GHz, 8GB RAM). Of course these figures will increase for more complex installations, but it has been demonstrated that the functionality for such preliminary installation design is operational and intuitive such that it can be easily operated with a quite steep learning curve. Also it is expected that reasonable response times of the computational operations are maintained also for larger installations.

## 9. Conclusions and further work

The developments of UHBR engines lead to higher operating temperatures and less space for the installation of engine and nacelle equipment and for maintenance accessibility. An optimisation methodology, built on a graph based approaches and efficient routing algorithms, has been implemented in a software tool (NEAT) that allows for flexible placement of equipment and automated routing of pipes, ducts and harnesses into the restricted volume of UHBR nacelles. A relatively simple case study of the installation of some electric generator and heat exchanger equipments in a representative nacelle KIZ has demonstrated the main functionality and the basic operation of this software tool. Efficient routing optimisation of dressings in the KIZ, requiring in the order of seconds compute time on a standard PC, has been shown.

Further developments of the functionality are considered in ongoing investigations, for example to incorporate more advanced constraints for the equipment installation, for example to better control separation between equipments, to account for temperature restrictions, to better handle bends and supports for dressings etc. Also more realistic installations studies with higher numbers of components and with more complex installation rules are investigated and will be reported in near future publications.

## Acknowledgements

The research leading to these results has been done as part of the NIPSE project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement N° 636218.

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