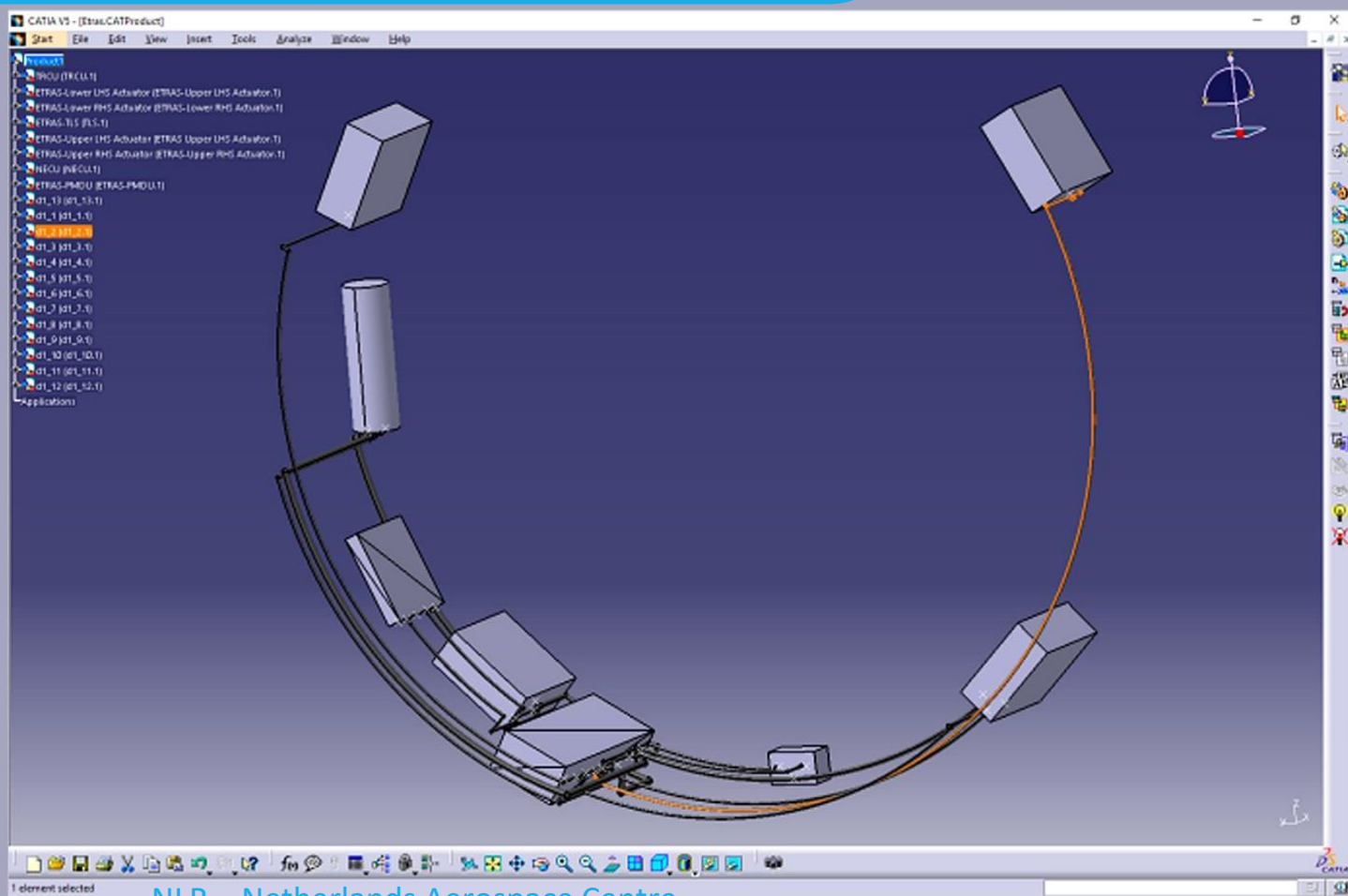


# A novel method for automated routing optimisation and equipment positioning in aero engine nacelles

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# A novel method for automated routing optimisation and equipment positioning in aero engine nacelles



*Illustration of the NEAT optimisation of UHBR engine nacelle equipment installation with all routed dressings.*

## 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. To address these challenges, better ways of developing integrated solutions for the IPPS are required. Improved technologies that allow the complete system to be developed and trade studies to be assessed have been investigated in the EU H2020 research project NIPSE. These technologies are aimed at finding solutions to

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UHBR

the challenges created by next generation of UHBR turbofan aero engines in terms of engine equipment integration.

## Description of work

In the NIPSE project, new optimisation methodologies aimed at optimising in 3D space have been investigated. This work has generated an optimisation tool (NEAT: Next generation engine Equipment Allocation Tool) that considers the placement of equipment as well as the automated routing of pipes, ducts and harnesses between the equipment in the nacelle. More specifically, the implementation of the advanced optimisation methodologies into an efficient software framework are considered, with focus on the integration with the CAD systems (such as CATIA) that are typically used in the industrial aero engine and nacelle design process. It is demonstrated for a design case from the NIPSE project of the so-called ETRAS (electric thrust reverser actuation system) installation that both efficiency and flexibility are ensured in this integration process.

## Results and conclusions

This paper presents the main results achieved in the ETRAS installation optimisation studies. The specifications of the considered installation and its equipment are given. The procedures that are followed and the resulting optimised installation solutions are described. The time to prepare the installation of the ETRAS case study is relatively short (around five minutes), thanks to the integration of the NEAT tool with the CATIA CAD system. The routing computation for all 13 harnesses in the ETRAS case requires about two minutes on a standard PC. The creation of the CATparts of the 13 dressings and the import into the global CATIA assembly requires about one minute. The overall time needed to realize this ETRAS installation study decreased from about 30min for the manual process to about 8min for the automated process.

## Applicability

Besides the optimisation methodology, also the software implementation is presented, in particular the software tool NEAT and its application to aero engine equipment installation design cases. The methodology is very flexible and well-suited for other industrial applications like harnesses routing and design for whole aircraft, fuselage or wing.

### GENERAL NOTE

This report is based on a presentation held at the AEGATS2018 conference, Toulouse, France, 23-25 October 2018.

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## Summary

This paper presents a feasibility study of concurrent use of state-of-the-art design and advanced optimisation methodologies for integrated engine equipment installation. The work focusses in particular on the integration with the CAD systems that are typically used in the industrial aero engine and nacelle design process. In early design phases of the Engine Build Unit (EBU) and Buyer Furnished Equipment (BFE) system installation, CAD systems like CATIA are used to define such system installation assemblies. The optimisation methodologies shall be interacting closely with the CAD assemblies, such that the equipment arrangements and the optimised installation assemblies can be efficiently transferred between the CAD and optimisation tools. It is demonstrated for a UHBR engine system installation design case that both efficiency and flexibility are ensured in this process. Fast and easy manipulation and optimisation of the equipment is achieved, while flexibility is ensured in this process through common generic interfaces (like Excel and ASCII STL files).

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# Contents

<b>Abbreviations</b>	<b>6</b>
<b>Keywords</b>	<b>7</b>
<b>Abstract</b>	<b>7</b>
<b>1 Introduction</b>	<b>7</b>
<b>2 Design case</b>	<b>8</b>
<b>3 NIPSE-ETRAS installation – challenges</b>	<b>8</b>
<b>4 NIPSE-ETRAS installation – approach</b>	<b>8</b>
<b>5 NIPSE-ETRAS installation – NEAT process</b>	<b>10</b>
5.1 Define equipments in the NEAT tool with the equipment editors	10
5.2 Import equipment from CATIA into NEAT	10
5.3 Define connections for dressings in the NEAT tool	12
5.4 Automatic routing of dressings in the NEAT tool	13
<b>6 NEAT Optimisation results: installation report file</b>	<b>14</b>
<b>7 NIPSE-ETRAS installation case study – General results and conclusions</b>	<b>14</b>
7.1 Description of the results found for the ETRAS case study	14
<b>8 References</b>	<b>15</b>

## Abbreviations

ACRONYM	DESCRIPTION
ASCII	American Standard Code for Information Interchange
BFE	Buyer Furnished Equipment
CAD	Computer aided design
EBU	Engine Build Unit
ETRAS	Eelectric thrust reverser actuation system
EU	European Union
GUI	Graphical user interface
H2020	Horizon 2020
IGES	Initial Graphics Exchange Specification
IPPS	Integrated power plant system
KIZ	Keep-in-zone
NEAT	Next generation engine Equipment Allocation Tool
NIPSE	Novel Integration of Powerplant System Equipment
PC	Personal computer
STL	Stereolithography
UHBR	Ultra high bypass ratio

# A NOVEL METHOD FOR AUTOMATED ROUTING OPTIMISATION AND EQUIPMENT POSITIONING IN AERO ENGINE NACELLES

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**KEYWORDS:** Optimisation, space allocation, graph theory, engine equipment, UHBR

## ABSTRACT:

This paper presents a feasibility study of concurrent use of state-of-the-art design and advanced optimisation methodologies for integrated engine equipment installation. The work focusses in particular on the integration with the CAD systems that are typically used in the industrial aero engine and nacelle design process. In early design phases of the Engine Build Unit (EBU) and Buyer Furnished Equipment (BFE) system installation, CAD systems like CATIA are used to define such system installation assemblies. The optimisation methodologies shall be interacting closely with the CAD assemblies, such that the equipment arrangements and the optimised installation assemblies can be efficiently transferred between the CAD and optimisation tools. It is demonstrated for a UHBR engine system installation design case that both efficiency and flexibility are ensured in this process. Fast and easy manipulation and optimisation of the equipment is achieved, while flexibility is ensured in this process through common generic interfaces (like Excel and ASCII STL files).

## 1. INTRODUCTION

Current technological developments in aircraft turbofan engines are aimed at better performance, among others, through increasing bypass ratio, like in the Ultra-High Bypass Ratio (UHBR) engine. In such new engine architectures, enhancements to the overarching integrated power plant system (IPPS) design are needed, in particular a shorter and slimmer nacelle. As a consequence, less space for the engine systems installation and for ventilation solutions is available. Moreover, higher operating temperatures and accessibility for maintenance further complicate the feasible arrangement of all the required engine equipment.

To address these challenges, more efficient ways of developing integration solutions for the IPPS are required. Optimisation methodologies that consider the complete system installation have been investigated in the EU H2020 research project NIPSE [1]. The optimisation approach considers

the placement of equipment as well as the automated routing of pipes, ducts and harnesses between the equipment. The optimisation approach is built on a graph based methodology involving efficient routing algorithms that rely on variants of the well-known Dijkstra's algorithm [2]. This automated routing process is achieved by applying dedicated optimisation methodologies to key variables of the installation. The development of the design and optimisation methodologies for the integrated equipment installation was recently presented in a previous publication [3].

This approach not only provides a potentially better answer (i.e. lighter installation solution) than current methodologies for equipment placement used in industry, but the automation aspect provides solutions faster allowing the development time of the IPPS to be reduced. The methodology is very flexible and well-suited for other industrial applications like aircraft harnesses routing and design.

This paper will present the implementation of the advanced optimisation methodologies into an efficient software framework, focussing in particular on the integration with the CAD systems that are typically used in the industrial aero engine and nacelle design process. In early design phases of the Engine Build Unit (EBU) and Buyer Furnished Equipment (BFE) system installation, CAD systems like CATIA [4] are used to define such system installation assemblies. The optimisation methodologies shall be interacting closely with the CAD assemblies, such that the equipment arrangements and the optimised installation assemblies can be efficiently transferred between the CAD and optimisation tools. For this purpose a Matlab [5] based software tool was developed, which was made executable for operation in Microsoft Windows [6] computer environments. It will be demonstrated for a UHBR engine system installation design case that both efficiency and flexibility are ensured in the optimisation process that is supported by this software tool. Fast and easy manipulation and optimisation of the equipment is achieved, while flexibility is ensured in this process through the use of common generic interfaces (like Excel [7] and ASCII STL files).

## 2. DESIGN CASE

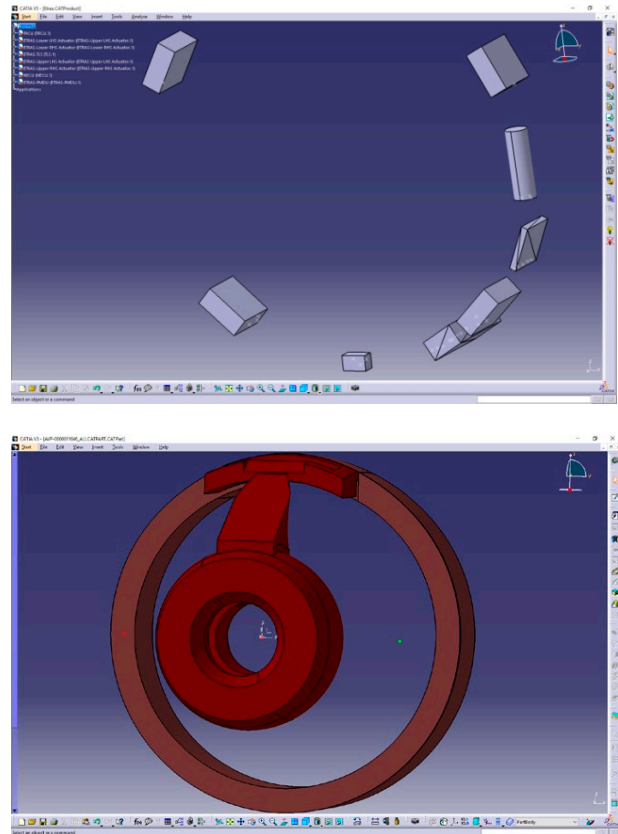
In this paper we will present in some more detail the implementation of the optimisation software framework. We will demonstrate for a design case from the NIPSE project of the so-called ETRAS (electric thrust reverser actuation system) installation that both efficiency and flexibility are ensured in this process.

The NIPSE project design case of the ETRAS that is considered here is a relatively simple installation example with only 8 equipments and simple box and cylinder shaped equipment geometries. It should be noted that also much larger numbers of more complex equipment geometries can be handled in the same way.

## 3. NIPSE-ETRAS INSTALLATION – CHALLENGES

If we consider the installation design of the ETRAS equipment in the UHBR engine's fan-zone, then typically a CAD system like CATIA is used for this. These equipments have to be positioned and interconnected inside the fan-zone of the UHBR engine's so-called keep-in-zone (KIZ). As an example, the ETRAS equipments considered in the NIPSE project design case are shown in *Figure 1* and are typically available as a CATIA assembly. The ETRAS contains 8 equipments that are located in the UHBR fan-zone. The identifiers for these 8 equipments are as follows (the exact meaning of these identifiers is not relevant for the present paper):

1. TRCU
2. ETRAS-LOWER LHS ACTUATOR
3. ETRAS-LOWER RHS ACTUATOR
4. ETRAS-PMDU
5. ETRAS-TLS
6. ETRAS-UPPER LHS ACTUATOR
7. ETRAS-UPPER RHS ACTUATOR
8. NECU



*Figure 1: Upper: Illustration of the NIPSE ETRAS-system equipments that are typically available as a CATIA assembly. Lower: illustration of the KIZ, with the large outer ring being the fan zone in which the ETRAS equipments shall be fitted.*

Some key challenges in this ETRAS-system equipment design process are:

1. How to easily position/move the ETRAS equipments inside the KIZ?
2. How to easily define so-called dressings (i.e. interconnections) between the ETRAS equipments?
3. How to easily route (and re-route!) dressings between the ETRAS equipment inside the KIZ?

## 4. NIPSE-ETRAS INSTALLATION – APPROACH

Of course, the positioning of each of the 8 ETRAS equipments inside the KIZ can be done very well in CATIA. But the definition and routing of dressings (e.g. harnesses) between these equipments is not necessarily done very well in CATIA. Especially if the equipments still have to be re-positioned and consequently all the dressings need to be re-optimised, i.e. re-routed.

In the NIPSE project, design and optimisation methodologies have been developed for the integrated equipment installation in UHBR engines [3]. These methodologies have been implemented

in a software tool called NEAT (Next generation engine Equipment Allocation Tool).

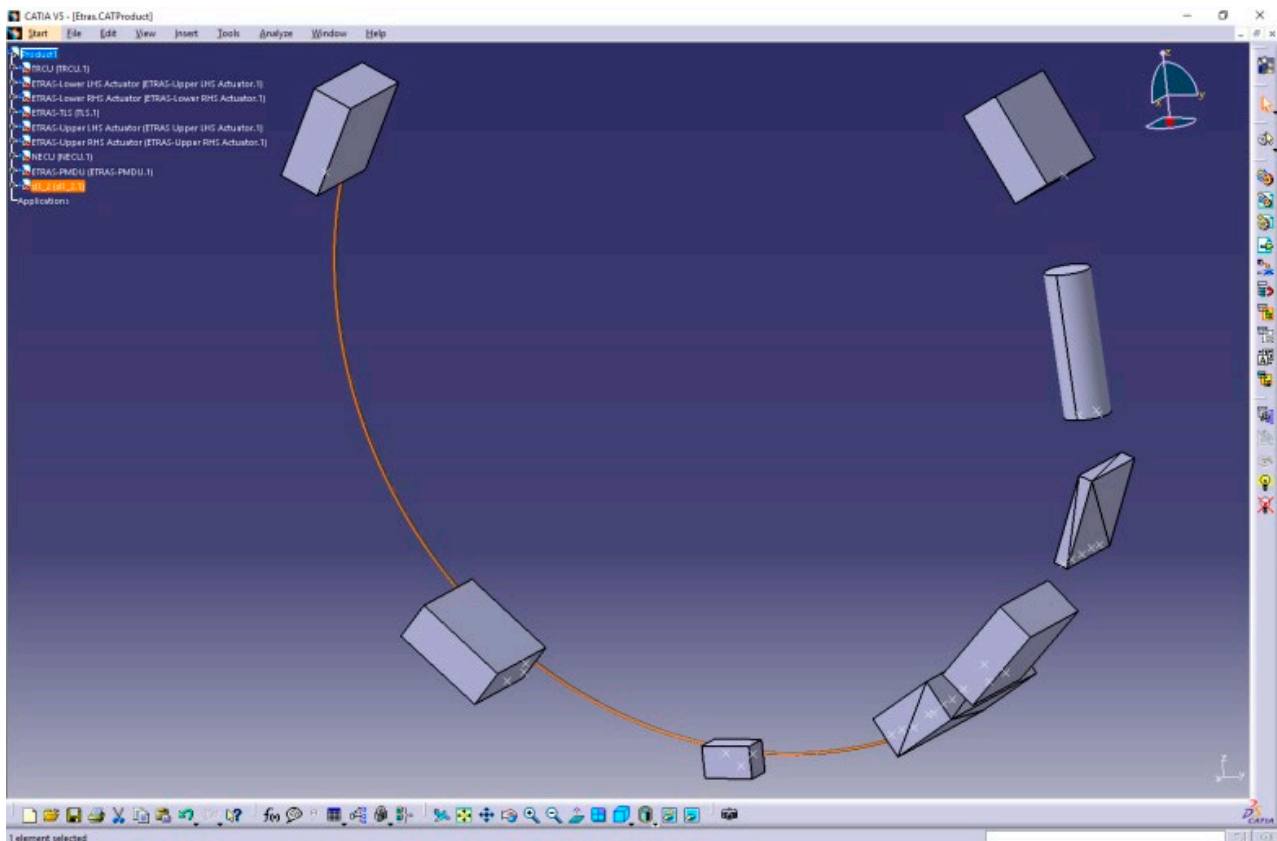
Because the automatic routing optimisation of dressings is well supported by the NEAT software tool, it is important to have efficient and flexible interfaces between CATIA and NEAT software environments. These interfaces allow for the easy exchange of equipments, dressings and assembly information between these tools. Besides the

interfaces, also a concise definition of dressings shall be supported: items like the name of the dressing, the equipment and connector from which and to which it connects, diameter and mass shall be identified. This is achieved in NEAT by the connection data table, for example shown in *Table 1* for one of the dressings with identifier “TRCU5-ULA1”.

*Table 1: Example of a NEAT connection data table for 1 dressing, including the items: the from- and to-equipments and connectors, the name, diameter and mass of the dressing.*

equipment1	connector_name	Name	Direction	connector_name	equipment2	diameter	mass/length
TRCU	TRCU-conn5	TRCU5-ULA1	[1,0,0]	ULA-conn1	ETRAS-UPPER LHS ACTUATOR	10	0.01

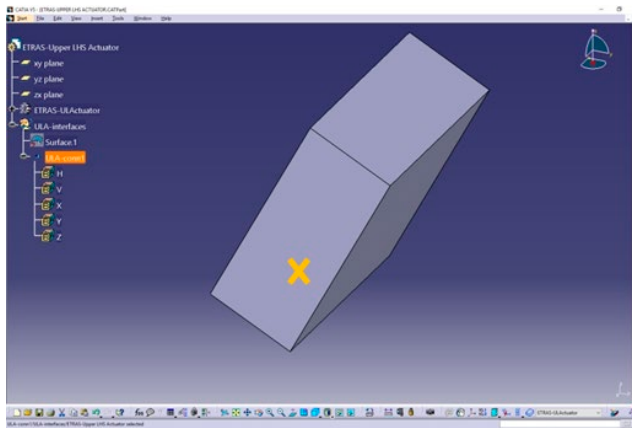
With this connection data table, the NEAT tool can directly calculate the optimised route for the dressing, inside the KIZ and between the specified connectors. The resulting routed dressing is also illustrated in the ETRAS assembly in CATIA in [4].



*Figure 2: Illustration of the routed dressing “TRCU5-ULA1” in the ETRAS assembly in CATIA.*

## 5. NIPSE-ETRAS INSTALLATION – NEAT PROCESS

The NEAT approach is to efficiently interface the NEAT tool with the CATIA design environment. In the ETRAS installation each of the 8 equipments, as shown in *Figure 1*, have connectors defined on their surface as illustrated for the ETRAS-UPPER LHS ACTUATOR equipment in *Figure 3*. These connectors can be defined in CATIA simply as geometric points with a name and location defined in the 3D local coordinate system of the equipment.



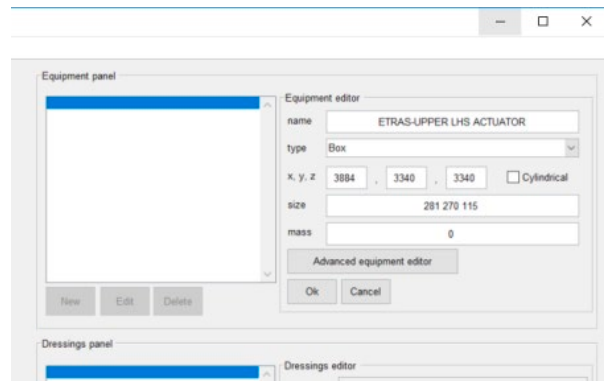
*Figure 3: Illustration of the ETRAS-UPPER LHS ACTUATOR equipment in CATIA. The connector “ULA-conn1”, as indicated by the orange cross, is defined in CATIA as a geometric point with location defined in the 3D local coordinate system of the equipment.*

The incorporation of the ETRAS equipments into NEAT can be achieved in 2 ways:

1. Equipments with simple geometry (i.e. box shaped) can be directly defined in the NEAT tool with the equipment editors;
2. Equipments with generic shape (i.e. box or any other shape) can be imported into the NEAT tool via STL and IGES files for equipment geometry and connectors; the equipment STL and IGES files can be directly exported from CATIA.

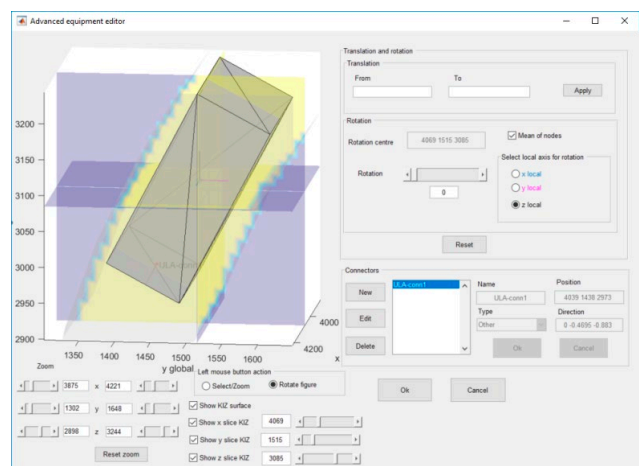
### 5.1. Define equipments in the NEAT tool with the equipment editors

The first option is convenient if simple equipments shall be quickly created in the NEAT tool. All the required equipment's properties, i.e. name, size, location and mass, can be specified in the NEAT equipment editor, see *Figure 4*.



*Figure 4: Illustration of the NEAT equipment editor, i.e. the Equipment panel in the top-right of the NEAT main GUI.*

Further detailed equipment properties can be specified in the NEAT Advanced equipment editor, see *Figure 5*. This editor allows to inspect and set the equipment's detailed location and orientation. The spatial positioning inside the KIZ is visually represented (by yellow and purple planes in plot window in *Figure 5*) and allows for detailed positioning of the equipment. Moreover, connectors of the equipment can be defined, edited and removed. By default, six connectors are automatically created for a box equipment: one on each face center. Also the connector properties (name, position, type and direction of connector) can be specified (e.g. as shown for the connector “ULA-conn1” connector in *Figure 5*).



*Figure 5: Illustration of the NEAT Advanced equipment editor for the ETRAS-UPPER LHS ACTUATOR equipment. This editor is presented as a pop-up window.*

### 5.2. Import equipment from CATIA into NEAT

The second option (import equipment from CATIA into NEAT) is necessary if complex geometry (i.e. other than box shaped) equipments shall be considered in the NEAT tool. Also (as is the case for the ETRAS installation) if a complete

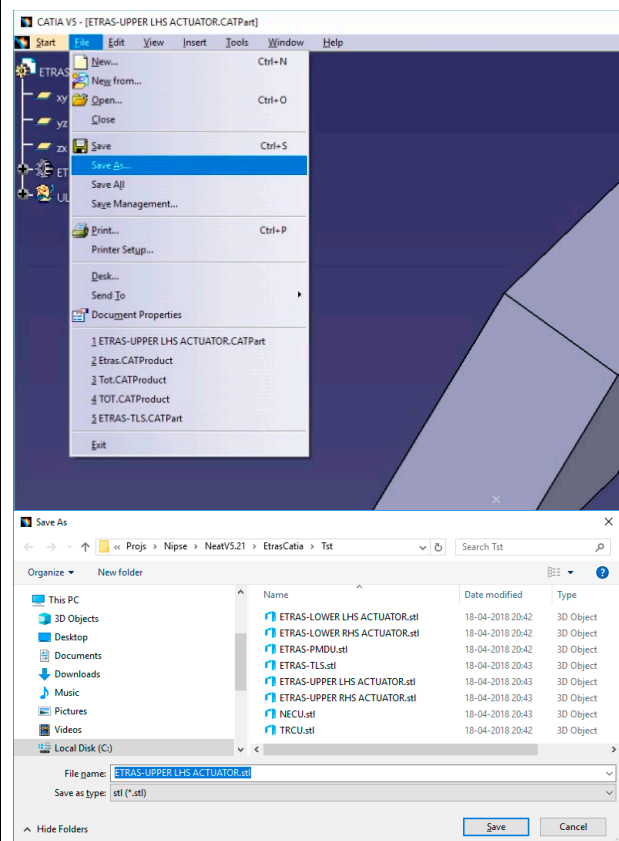


installation assembly is available in CATIA, this option is suitable because all the equipment's properties (name, size, geometry, position, orientation, connectors) that are available in CATIA now are automatically adopted into NEAT from CATIA. The process has two straightforward steps:

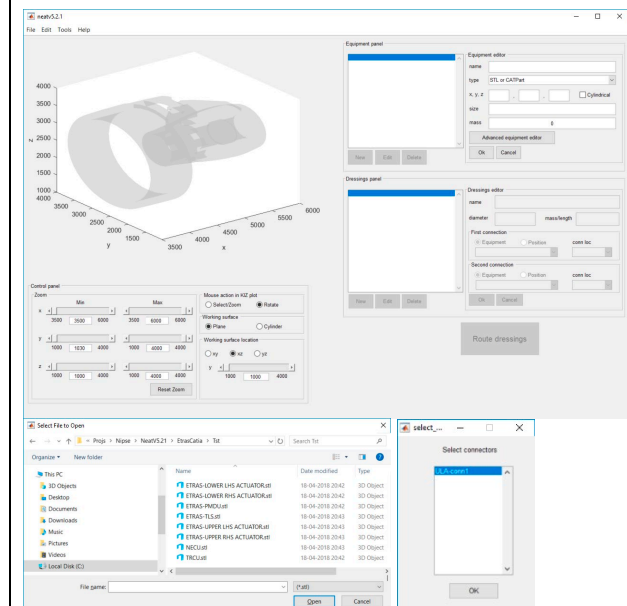
1. In CATIA: save equipment as STL file and save connectors as IGS file;
2. In NEAT: create new equipment, select type STL or CATPart, open the STL file that was saved from CATIA, select the associated connectors.

This process is briefly illustrated for the ETRAS-UPPER LHS ACTUATOR equipment in *Figure 6*.

**Step 1: In CATIA: save equipment as STL file and save connectors as IGS file:**



**Step 2: In NEAT: create new equipment, select type STL, open the STL file, select the connectors:**



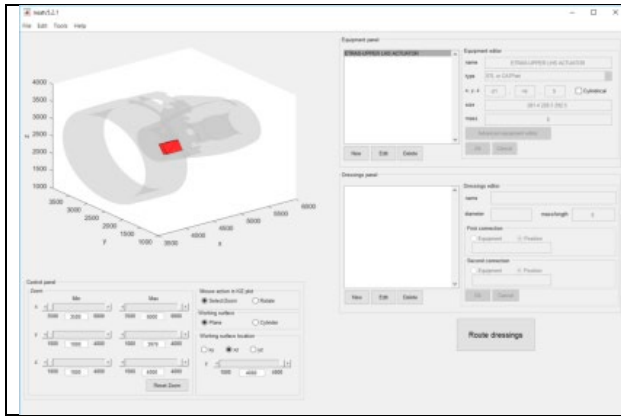


Figure 6: Illustration of the process to import equipment from CATIA into NEAT.

### 5.3. Define connections for dressings in the NEAT tool

With both options for the equipment creation, subsequently each of the 8 ETRAS equipments can be created in NEAT. Once all the equipments, with their associated connectors, are correctly positioned in the fan zone, the desired connections between equipments can be defined with the NEAT dressings editor. For example for the TRCU5-ULA1 connection this is illustrated in the Figure 7.

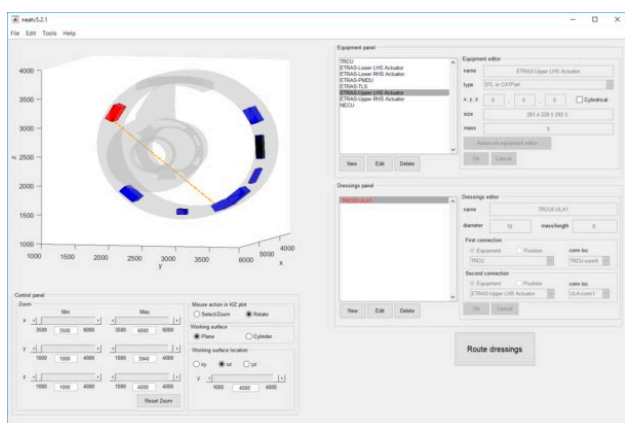
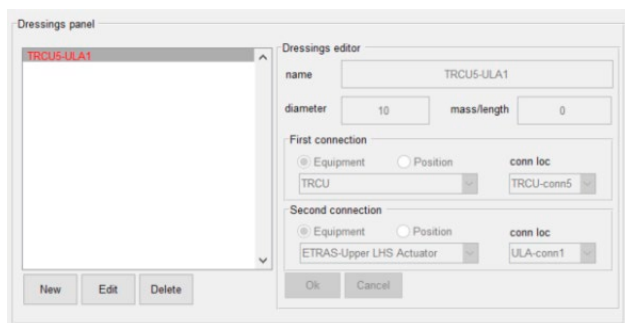


Figure 7: Left: Illustration of the NEAT dressings editor, i.e. the Dressings panel in the lower-right of the NEAT main GUI. As an example the specifications for TRCU5-ULA1 connection are shown: From equipment: TRCU; Connector:

TRCU-conn5; To equipment: ETRAS-UPPER LHS ACTUATOR; Connector: ULA-conn1; Diameter: 10mm; mass/length: 0 (default value). On the right the resulting connection is shown (the orange line) in the NEAT main GUI plot window.

Once the connection for the dressing is defined, the resulting configuration, containing all the ETRAS equipments and connections, can be exported to an Excel configuration file. In this file, the Equipments sheet contains all the data of the 8 equipments in the ETRAS installation and the Dressings sheet contains all the data of the connections for dressings in the ETRAS installation. This is shown for the TRCU5-ULA1 connection in Figure 8.

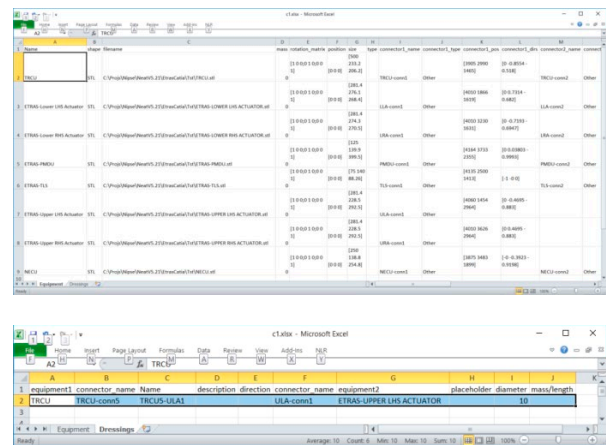
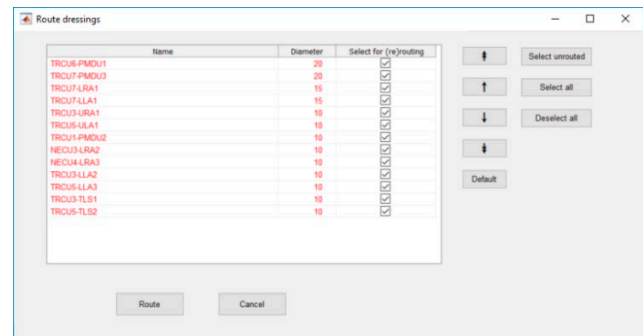


Figure 8: Illustration of the NEAT Excel configuration file. Upper: The Equipments sheet contains all the data of the 8 equipments in the ETRAS installation. Lower: the Dressings sheet contains all the data of the connections for dressings, in this case only the TRCU5-ULA1 connection of the ETRAS installation is shown.

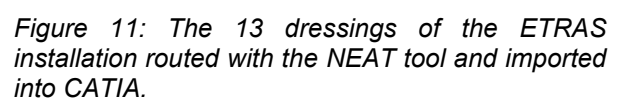
In the Excel configuration file the connections for dressings can be further edited, added or deleted directly in Excel. The further updated Excel configuration file can then be imported back in the NEAT tool. This is shown for all the 13 connections in the ETRAS installation in Figure 9. It should be noted that, of course, all the connections for dressings can also be directly defined in the dressings editor of the NEAT GUI.





#### 5.4. Automatic routing of dressings in the NEAT tool

For the ETRAS case, the routing computation for all 13 dressings requires about two minutes on a standard PC (i7-7820HQ CPU @ 2.9GHz). The resulting installation (*Figure 10*) can be easily further modified in NEAT, re-routed, saved and exported to CATIA. The exported dressings can be directly imported into CATIA, as shown in *Figure 11*.



## 6. NEAT Optimisation results: installation report file

If the routing optimisation in NEAT is completed successfully, all relevant data of the optimised ETRAS installation (i.e. all equipments and dressings) can be saved in a report file. This is an Excel file, containing also an Equipments sheet with all the data of the 8 equipments in the ETRAS installation and a Dressings sheet with all the data of the 13 dressings in the ETRAS installation, as shown in *Figure 12*. Currently the data that is saved in the report file are the Name, Mass, Zone and Max. air temperature for the equipments, and the Name, Type, Diameter, Length, Volume, Mass and Max. air temperature for the dressings.

	A	B	C	D	E
	Name	Mass	Zone	Max. air temperature	
1	TRCU		0 fan zone	77	
2	ETRAS-Lower LHS Actuator		0 fan zone	77	
3	ETRAS-Lower RHS Actuator		0 fan zone	77	
4	ETRAS-PMDU		0 fan zone	77	
5	ETRAS-TLS		0 fan zone	77	
6	ETRAS-Upper LHS Actuator		0 fan zone	77	
7	ETRAS-Upper RHS Actuator		0 fan zone	77	
8	NECU		0 fan zone	77	

	A	B	C	D	E	F	G	H
	Name	Type	Diameter	Length	Volume	Mass	Max. air temperature	
1	TRCU3-URA1	Other	10	2335	183390	0	77	
2	TRCU5-ULA1	Other	10	2917	229101	0	77	
3	TRCU6-PMDU1	Other	20	1606	504540	0	77	
4	TRCU7-PMDU3	Other	20	1843	578996	0	77	
5	TRCU1-PMDU2	Other	10	2000	157080	0	77	
6	TRCU7-LRA1	Other	15	621	109740	0	77	
7	NECU3-LRA2	Other	10	621	48773	0	77	
8	NECU4-LRA3	Other	10	799	62753	0	77	
9	TRCU7-LLA1	Other	15	1271	224604	0	77	
10	TRCU3-LLA2	Other	10	1560	122522	0	77	
11	TRCU5-LLA3	Other	10	1332	104615	0	77	
12	TRCU3-TLS1	Other	10	918	72100	0	77	
13	TRCU5-TLS2	Other	10	720	56549	0	77	

*Figure 12: Illustration of the report file of the ETRAS installation. On the left: the Equipments sheet with all the data of the 8 equipments in the ETRAS installation. On the right: the Dressings sheet with all the data of the 13 dressings in the ETRAS installation.*

## 7. NIPSE-ETRAS installation case study

### 7.1. General results and conclusions

An installation optimisation methodology based on graph theory has been implemented in the NEAT software tool [3]. The optimisation methodology supports flexible placement of equipment and

automated routing of pipes, ducts and harnesses into the restricted volume of UHBR nacelles. The efficient integration of NEAT in the installation design process with CATIA has been illustrated for the ETRAS installation. The automatic routing of dressings in the KIZ requires in the order of seconds compute time on a standard PC, and in the order of minutes for the routing of all 13 dressings in the ETRAS installation.

### 7.2. Discussion of the results found for the ETRAS case study

The ETRAS case study presented above is a relatively simple installation since it takes into account only eight equipments with simplified geometries located in the fan zone and there is no other equipment installed in this zone. Nevertheless it allows assessing the benefits of the optimisation tool and identifying improvements that may be incorporated in the future versions.

Thanks to the CATIA plug-in version of the NEAT tool, the time to prepare the installation of the ETRAS case study is relatively short (around five minutes), then as mentioned previously the calculation time for the 13 dressings is around one or two minutes. Finally, an additional minute is needed to create CATpart of the 13 dressings and to import them in the global installation in CATIA. If the same 13 dressings are performed manually directly in CATIA, it takes approximately 30min. The time to route these 13 dressings is thus decreased by 75% (from 30min to 8min).

The time to realise the installation is not the only criteria to assess the performance of the optimisation tool. The pertinence of the routings proposed by NEAT tool is also a key criteria. When analyzing the routings proposed by NEAT tool for this ETRAS case study, it appears that the main constraints that are incorporated in the NEAT tool are correctly taken into account, i.e.:

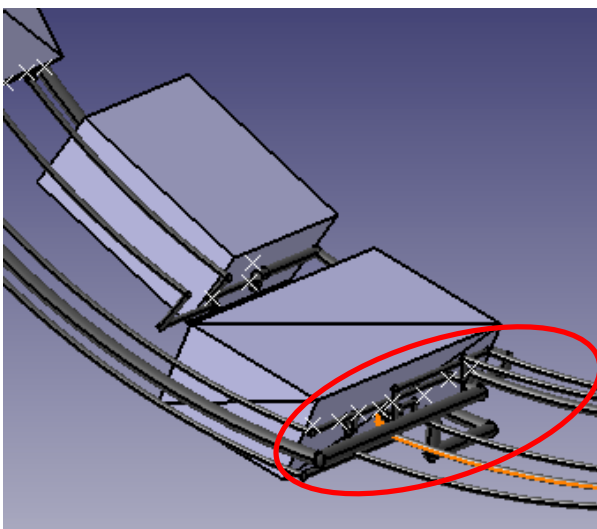
- ✓ All dressings are inside the KIZ
- ✓ There is no clash/collision between dressings
- ✓ The number of bends are minimized
- ✓ The total length seems to be the shortest.

Nevertheless the dressings from the NEAT tool cannot be directly used for termination of preliminary design activities since some modifications are needed:

- Minimum values for bending radii of the dressings are not yet taken into account by the optimisation process in the NEAT tool. In fact, as a simplification, currently the minimum possible bending radius (i.e. equal to the cross-sectional radius) is always used for each bend.
- Dressings have to be attached to engine structure (i.e. casing) while some dressings that are routed by the NEAT tool are far from

the casing since the NEAT algorithm is defined to find the shortest dressing. This aspect has to be implemented as additional constraint in the algorithm.

- Some small clashes or low clearances have been identified between dressing and equipment. These small clashes may be linked to the discretization of the equipment done by the tool. The minimum grid size currently used in the NEAT tool is 10mm, which can generate clashes of similar size. This point is also due to the fact that the present case studies have not been performed on the latest version of the NEAT tool. A new version of the NEAT tool has been developed by NLR, in which the operator can define which clearance is wanted between two dressings and between dressing and equipment, while in the NEAT version used for these tests these clearances were set to zero and could not be modified.
- As the dressings are calculated in a sequential way (one by one), there are some cases where one of the first dressing (by default the one with the biggest diameter) is routed in front of other connectors on the equipments, which may result in undesired routes for the dressing attached to these connectors. These dressings can be corrected manually by post-processing in CATIA (as shown in *Figure 13*). The other solution could be to perform a second iteration of the NEAT tool, in which the dressing that creates the issue is constrained by the addition of a point that is manually positioned.



*Figure 13: Illustration of area requiring modifications in ETRAS case study.*

As a conclusion from this ETRAS case study we find that some of the dressings require some manual corrections by post-processing in CATIA. But even taking into account these manual corrections, the potential time saving when using the tool in comparison to the complete manual routing (and re-routing) process in CATIA is

substantial. The number of manual modifications that are currently needed can be drastically reduced further if the improvements described above can be successfully incorporated. The automated routing process allows for testing and comparing quickly a lot of configurations (i.e. modifying the location of equipment), which is something very valuable in the conceptual design phases of an IPPS in order to identify the most optimised configuration in terms of weight, cost, maintenance.

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