PASTA – Parametric Approach for Space Transplanet hAbitations.

A generative powered design process for internal configurations in spaceships

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This paper focuses on the Space transplanet habitations, or spaceships, that will host astronauts during their transfer to other celestial bodies. In this enterprise, the transfer phase is the most critical in resource shortages (e.g., air, water, room), making it harsh under habitability perspectives. The increasing number of involved scientific disciplines has raised difficulties in managing the design process, and the traditional design strategies have collapsed under the growth of complexities.

PASTA proposes an implementation of generative design for the spaceship's internal configurations. This framework focuses on the multi-objective and performance-driven design process, allowing a designer to explore multiple layouts of a complex 'building' such as a spaceship. It encodes habitability needs in an unusual environment and estimates each configuration performance among intertwined needs, including adjacency relationships, by an evaluation system. As a result, PASTA can automate part of the spaceship design tasks and provide decision-making support by evaluating generated solutions, improving the handling of complexities in the design process.

Keywords: *Space Architecture, Parametric Design, Generative Design, BIM.*

INTRODUCTION

The increasing enthusiasm for planetary colonisation has energised visionary projects for extra-terrestrial environments. After the expertise in living in the Low Earth Orbit since the 1960s, Space agencies across the world are investigating the feasibility of establishing a permanent settlement in farther destinations (Nassey & Welch, 2019).

In this enterprise, the transfer phase is the most critical under the habitability perspective, and the spaceship is the only dwelling able to provide shelter from the lethal surrounding environments for the astronauts (Whitmore et al., 2013). The must-be-dealt issues include adverse effects, resource shortages (e.g., air, water, food, room), and the astronauts' human factors during the mission, which could last for several months and even years. During this period, it has been observed that layout considerations, rather than overall internal volume, influence most of the psychological and behavioural health stressors (Simon et al., 2012). It is then necessary to consider the dualism of Spaceships to be both vehicle and habitation, providing necessary wellness and comfort to their users (Zhu et al., 2020).

The next-generation Space missions require prompt solutions and alternatives according to variables such as Spaceship information, crew size, and mission objectives (ESA, 2020). With the increasing number of the involved scientific disciplines, the management of the complexities during the design process became difficult, and adequate design strategies are required.

There are many parametric and generative design implementations in the literature for multi-objective optimisation. This approach transforms design problems into mathematical optimisation exploiting stochastic and metaheuristic algorithms to discover possible combinations. Under this circumstance, the design process can be expressed as a sequence of tasks and then be automated.

On the other hand, AEC industries propose BIM methodology to deal with building components and/or their assemblies. BIM can bring several benefits during the design process based on knowledge databases, embodying them as efficient decision-making support.

STATE OF THE ART

The application of generative design for spaceship *volume* planning has been tested by SOLV – Spacecraft Optimisation Layout and Volume, founded by NASA (Thaxton et al., 2017). It is a computational model able to perform geometrical and spatial optimisation considering tasks, and it can be used during the early design phases to estimate a spaceship's habitat volume. This work adopts a "bottom-up" approach and aims to determine the critical volume of a Spaceship based on mission objectives.

On the other hand, spatial planning from an existing geometry has been tested in the work of Nagy et al. (2017). In particular, a generative approach has been adopted to plan the internal distribution of a building and a set of selected performances has supported the individuation of valuable configurations.

OBJECTIVES

This work proposes better liveability in Spaceships during long period missions through the optimisation of the internal configuration. In particular, PASTA – Parametric Approach for Space Transplanet hAbitations, is a multi-objective and performance-driven workflow able to organise the inner rooms of a Spaceship, considered a complex building system, proposing satisfying alternatives. Under these perspectives, a Spaceship represents an interesting building type and a case study with stringent conditions and specific parameters, requiring efficient optimisation.

PASTA proposes a parametric workflow based on the generative design approach and wants to estimate the performances of each configuration among the mutual conflicts by an evaluation system.

METHODOLOGY

Spaceships able to transfer humans to long-distance destinations are still under development. Nevertheless, PASTA's primary interest is the internal configuration of a spaceship, and it relies on parametric inputs. It is then valid, to a certain extent, for any cylinder-form spaceship. For demonstrative purposes, it has been considered as a case study the second stage of Spacecraft developed by Space X called *Starship* (Figure 1).

The present work has adopted a BIM-based platform able to perform generative studies, in this case Revit 2023. The coding part has been achieved by Revit integrated Visual Programming Language Dynamo (used packages are: BimorphNodes, Clockwork, LunchBox, Rhythm). It has provided interfaces to enable data exchange and communications between involving experts. Data inputs (e.g., general information, requirements and evaluation parameters) are loaded from spreadsheets, while the geometric ones by their file path on the Operating System.

Habitability needs and design intentions have been encoded in Dynamo, defining the generative structure. As mentioned, the present work focuses on optimising a spaceship's internal configuration. During this process, the available room has been divided into standard modules or Functional Space Units – FSU, each one hosting a particular mission task. It has been considered mission tasks individuated by Wickman & Anderson (2009), which are: private area, work, medical/health, food preparation and entertainment.

Figure 1:
Starship SN9 sitting on its launch pad (Credit Creative Commons).

Surface requirement of each task has been expressed as dependent of the crew number (sqm/ number of crew) and reported in Table 1. For the Entertainment FSUs a different method has been adopted (explained in the dedicated section). Then the FSUs are collocated in stochastic way, in order to explore potential configurations.

Table 1
General information

Key	Value
Storey Height (m)	2,70
Landing storey	30
Technical storeys number	2
FSU area (sqm)	12,5
Req. surf. Private (sqm/person)	12,5
Req, surf. Work (sqm/person)	15
Req. surf. Greenh. (sqm/person)	5
Req. surf. Health/Med (sqm/person)	3
Req. surf. Cooking (sqm/person)	5

An evaluation system has been designed basing on a set of criteria to skim off satisfying configurations. The idea is a decision-making support for the generated configurations, that helps the designer to choose the most optimal ones.

The definition of the generative structure, evaluation system and the parameters of the generative process are reported thereafter, and the overall workflow is shown in Figure 2.

Generation structure

The spaceship's geometric input is provided by an external 3D file. An axis can be deduced according to the propulsion direction during the transfer phase. This could also give a sense of orientation (up and down) under alternate gravity conditions. Adequate propulsion may provide a fictitious force that can simulate gravity, keeping astronauts' physical and physiological wellness (Connors & Harrison, 1985).

A spaceship is composed of several systems (e.g., communication, HVAC, mechanical propulsion), and many of them are crucial for its correct functionalities. It is reasonable then that room hosting the crucial functions should be fixed from the outset.

Figure 1Therefore, as shown in Figure 3, offset from the top and bottom sides have been taken to exclude space dedicated to tanks and engines from the internal configuration's optimisation. The FSUs should be inside of the available volume, and the latter has been divided into storeys of 2,70m in height (Table 1).

The present workflow has been designed for spaceships featured with limited extension in their transversal sections. In the case of the *starship*, the latter are composed mainly of circular surfaces of 4,50m in radius. It has been considered the internal area of 50 sqm and decided to collocate 4 FSUs per storey. Each FSU is then featured with 12,50 sqm and is identified with an ID number that will be used during its collocation.

Above mentioned parameters have neem calculated according to Equation 1.

Equation 1
Storeys and internal units' generation

$$Height_{Available} = Height_{Overall} - Offset_{Top} - Offset_{Bottom}$$

$$Number_{Storeys} = Height_{Available} \,/\, Height_{FUs}$$

$$Number_{FSUs} = Number_{Storeys} \times 4$$

The number of crews directly influences a mission's consumable resources, including room arrangement. It has been pointed out the importance of a good equilibrium between private and public areas during long period Space missions (Häuplik-Meusburger & Bishop, 2021). In this research, private rooms have been provided for each astronaut in respect of due privacy. The defined surface for FSUs satisfies NASA's study concerning factors that impact habitable volume requirements (Simon et al., 2012).

According to the now available technologies, consumables - like air and water - can be recycled from biological wastes. The food supplies must rely on storage before the departure. Nevertheless, in the perspective of sustainable Space explorations and colonisation, it is a vital need the production of food during the mission. Although Space greenhouses are still under development, it has been demonstrated that their presence could be pleasant for the astronauts as internal gardens (Häuplik-Meusburger et al., 2014). Hence FSUs hosting greenhouses have been implemented in this work.

The technical and the landing storeys, where is collocated the hatch and where are stored the spacesuits, are defined through the external spreadsheet (Table 1).

Corresponding FSUs have been created as Revit Family, then imported, collocated and set up in Dynamo. The collocation of the FUs happens stochastically and it is enabled by a *seed*. Equation 2 and Figure 3describe the distribution logic of FSUs in the available volume.

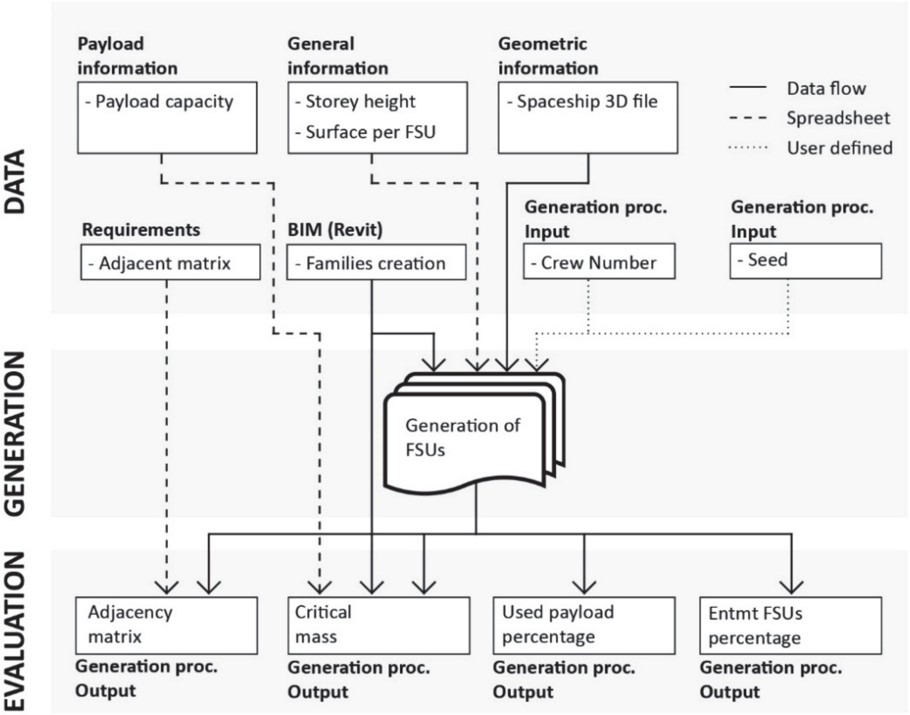
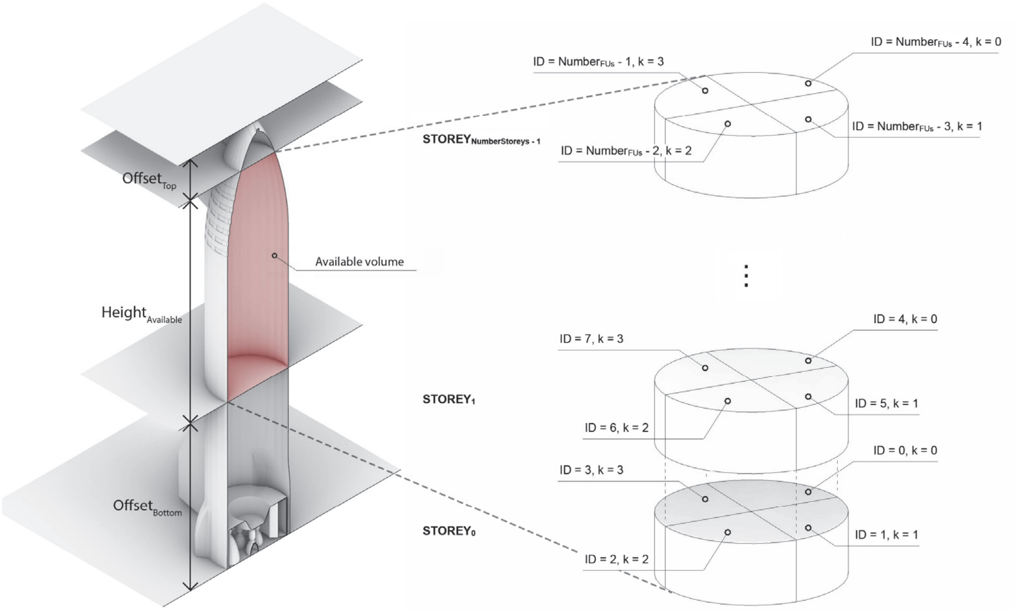


Figure 2
PASTA's Workflow

Figure 3
Available volume
and distribution
logic of FUs



Equation 2
Distribution logic of
the FUs.

$$ID_n = [0, 1, \dots, Number_{FUs} - 1]$$

$$Collocation_{Storey} = Floor(\frac{ID_n}{4})$$

$$Collocation_{Rotation} = k \times 90°$$
$$k = ID_n \; mod \; 4$$

Design of the evaluation system

The combination between parameters can bring a vast number of configurations. Many of these are results of mere math computations and have no design validity. The evaluation could require unnecessary time and energy consumption if based only on the designer's manual analysis. A consolidated strategy to skim off satisfying outcomes is based on the objective and evaluation of a set of performance criteria. This method can effectively support designers during the decision-making process, helping them to pick out the most valuable configurations for further analysis.

In this research, the following criteria have been selected as the objectives, i.e., the output of the generative process:

Adjacency matrix evaluation

It has been defined that closeness between many FUs can generate positive vibes while others do the opposite. This evaluation has been made by an adjacent matrix imported through the spreadsheet. This strategy expresses the relationship between FUs with a numerical 0 to 3 scale where 0 represents unpleasant connections, while 3 are the desirable ones (Table 2).

The evaluation is supported by data management of the FUs' family in Revit. This operation plays a crucial role in recognition of FUs, and then their relationship with others.

Table 2
Adopted adjacency matrix

	Private	Work	Greenh.	Health	Cooking	Entmt.
Private	3	0	2	1	0	2
Work	0	3	2	1	1	1
Greenhouse	2	2	1	1	3	2
Health	1	1	1	1	1	1
Cooking	0	1	3	1	2	3
Entmt.	2	1	2	1	3	3

In this research there have been created 6 Revit families, corresponding to each FSU. For each of these, its collocation has been detected and then the two adjacent FSUs in the same storey. According to the adjacency matrix, their connection has been rated (RateFSU$_m$ or RateFSU$_l$). This process must be performed for all the FSUs and the final output is the summation of the score from each connection's evaluation (Equation 3). The maximum and the minimum score can be calculated considering all best or all worst connections.

The score of each configuration under this criterion is expressed in a 0-100 scale using the *MapTo* node in Dynamo.

$$O1\_AdjMtx = \sum_{0}^{n} ConnEva\_FUs_n$$

$$n = [0, 1, \dots, Number_{FSU} - 1]$$

$$ConnEva\_FSU_n = RateFU_m + RateFU_l$$

$$if\ n \bmod 4 \neq 0, \qquad m = n - 1, \qquad else\ m = n + 3$$

$$if\ n \bmod 4 \neq 3, \qquad l = n + 1, \qquad else\ m = n - 3$$

Equation 3
Adjacent Matrix evaluation

Critical mass evaluation

Configurations generated in the BIM environment are featured with physical properties, including the components' mass. The number of FSU varies according to the crew number (see Equation 1). It is then useful to evaluate the total mass for each configuration and compare it with the spaceship's maximum payload capacity.

For demonstrative purposes, this research relies on floors and wall panels adopted in the crew quarter of the International Space Station. In particular, they are made in ultra-high molecular weight polyethylene (UHMWPE), and aluminium for the structure, which is approximately 65 mm thick (Broyan et al., 2009).

On the other hand, it is reasonable that FSUs that host different activities are featured with their own equipment and furniture, which bring varying loads for each FSU. Scientific equipment and furniture onboard are often developed *ad hoc*. Their weights have been considered in this research even though the number and type of equipment are not specified. In this case, it has been assumed parameter values for loads (Table 3), which can be replaced with actual ones in real circumstances. This workflow does not consider any gravity variation. More accurate studies are required to evaluate the latter, especially during the launch phase.

Table 3
FSUs' load

Parametrical loads for FSUs	Value
Private (kg/sqm)	150
Work (kg/sqm)	400
GH (kg/sqm)	300
Health/Med (kg/sqm)	400
Cooking (kg/sqm)	200
Entertainment (kg/sqm)	150
Landing and Tech. (kg/sqm)	400

The load of each FSU is embedded in its family information in Revit. After the generation and the collocation of FSUs, their load value is extracted from Revit and multiplicated by the corresponding quantity ($Number_z$).

The evaluation of the overall weight over the payload capacity (considered value: 125'000 kg) can be expressed by Equation 4.

Evaluation of used payload volume

The evaluation of the used payload volume plays an important role in the mission economy. Overestimating it brings to the payload failure while underestimating it would be wasteful. In this vein, this criterion evaluates the amount of generated FSUs in each configuration over the spaceship's maximum payload capability. It is noteworthy that

Equation 4
Evaluation of the
critical mass

$$O2\_CrtMass = \frac{\sum_S(Weight_S) + \sum_z(Weight_z)}{Payload_{capacity}}$$

$$Weight_S = Weight_{Floors_S} + Weight_{Walls_S}$$
$$S = [0, 1, \ldots, Number_{Storeys} - 1]$$

$$Weight_z = Load_z \times NumberFSU_z$$
$$z = [1, 2, 3, 4, 5, 6\,]$$

Number_FU1: Number of FUs for private area
Number_FU2: Number of FUs for work area
$Number_{FSU3}$: Number of FUs for Greenhouse
$Number_{FSU4}$: Number of FUs for Medical/Health
$Number_{FSU5}$: Number of FUs for food prep.
$Number_{FSU6}$: Number of FUs for Entertainment

Equation 5
Used payload
volume evaluation

$$O3_{PlUtls} = \frac{Volume_{configuration}}{Volume_{Payload}} =$$

$$= \frac{\sum_z(NumberFSU_z) \times \cancel{VolumeFSU}}{Number_{FSU} \times \cancel{VolumeFSU}} =$$

$$= \frac{\sum_z(NumberFSU_z)}{Number_{FSU}}$$

Equation 6
Evaluation of the
Entmt FUs
percentage

$$NumberFU_6 = NumberFU_s - \sum\nolimits_z (NumberFU_z)$$
$$z = [1, 2, 3, 4, 5\,]$$

$$O4\_EntmtPerc = \frac{NumberFU_6}{\sum_z(NumberFU_z)}$$

Table 4
Generative process
input list

Input name	Value
Crew number	0 – 50, step 1
Seed	0 – 50, step 1

Table 5
Generative process
objective list

Output name	Source
Adjacent Matrix	Equation 3
Critical mass	Equation 4
Used payload volume	**Fehler! Verweisquelle konnte nicht gefunden werden.**
Entmt FSUs perc.	Equation 5

the volume value of FSU can be found on both sides of the fraction and can be simplified according to Equation 5.

In the present research, the number of FSUs (except those for Entmt) is strictly dependent on the number of crew members. This means that this criterion evaluates the feasibility, in terms of crew number, considering the spaceship payload capabilities.

Entertainment (Entmt) FUs percentage
Compared with other FSUs, the number of entertainment FSUs does not depend on the number of crew. This is assigned among the remaining space after the definition of other FSUs, according to Equation 6.

$Number_{FU6}$ could be negative if the crew number exceeds the spaceship's capability. In these cases, the combination of parameters fails and the generated configuration will be discarded.

Generation process and its parameters

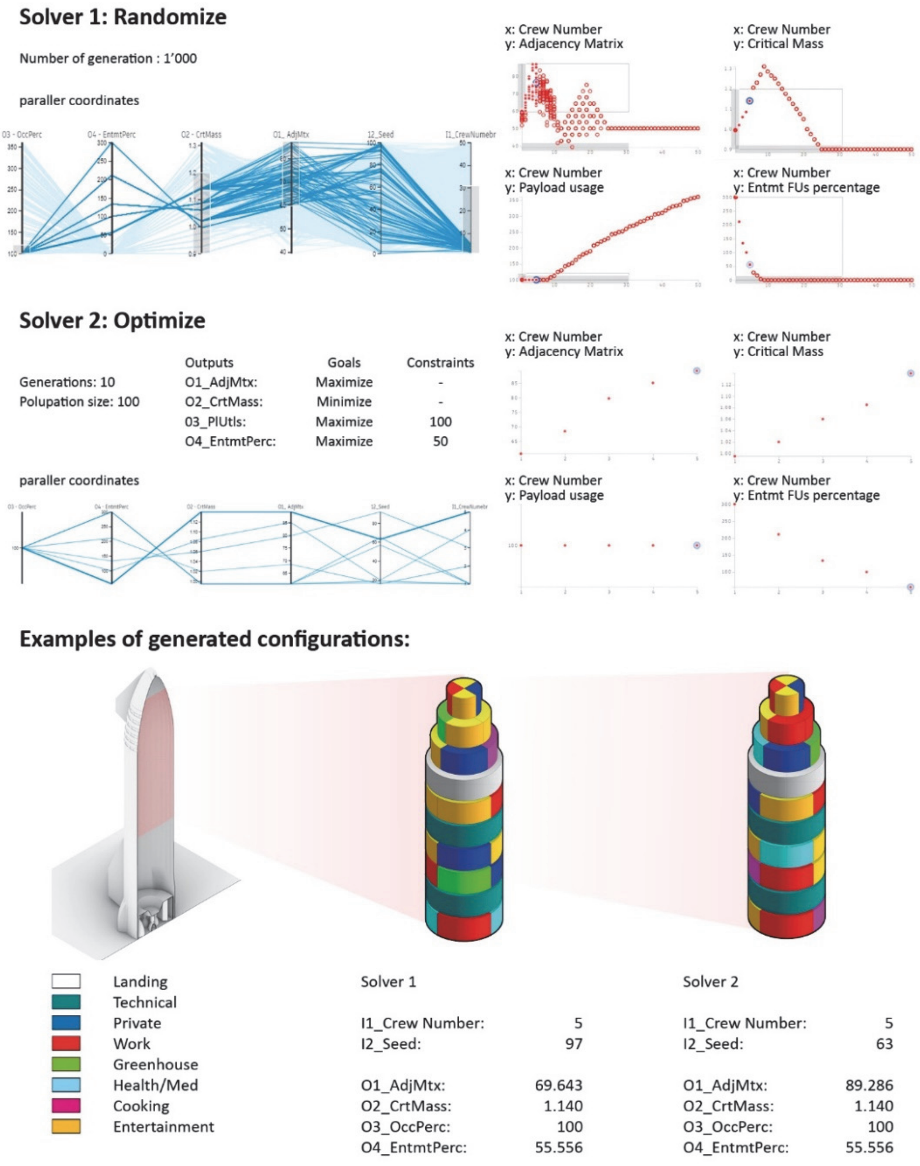
The present research uses Revit 2023 integrated generative studies component. After defining the generative process' structure, it has been established inputs and outputs.

The first ones are directly defined and are related to outputs by the above mentioned math operations. Their values permutate within a range, affecting the result of the generations. In the present research, it has been considered as input the seed of the randomise process during the FSUs collocation and the number of crew.

The generative process' outputs are objectives of the generation process and they match with the evaluation criteria in the previous section. Inputs and outputs of the generation process are reported in Table 4 and Table 5.

In this research, two types of generative process *solvers* have been performed: "randomise" and "optimise". The first varies inputs stochastically within the assigned range, generating a defined number of design options. In the second type of

Figure 4
Generation results



Generations: 10
Polupation size: 100

Outputs	Goals	Constraints
O1_AdjMtx:	Maximize	-
O2_CrtMass:	Minimize	-
03_PlUtls:	Maximize	100
O4_EntmtPerc:	Maximize	50

Solver 1	
I1_Crew Number:	5
I2_Seed:	97
O1_AdjMtx:	69.643
O2_CrtMass:	1.140
O3_OccPerc:	100
O4_EntmtPerc:	55.556

Solver 2	
I1_Crew Number:	5
I2_Seed:	63
O1_AdjMtx:	89.286
O2_CrtMass:	1.140
O3_OccPerc:	100
O4_EntmtPerc:	55.556

solver, the generating process is based on the defined outputs and each *generation* uses input configuration from the previous one to optimise, or *evolve*, new design options. In this case, it is required to specify the optimisation process's goal (maximised or minimised).

DISCUSSION, FUTURE DEVELOPMENT AND CONCLUSION

PASTA is a workflow based on the generative design approach able to carry out a Spaceship's internal configuration optimisation. It skims out genuine configurations through an evaluation system and BIM to lead the performance optimisation. During this process, FSUs' identity has been manually set up during the corresponding family's creation. In future, this process may be performed by a spatial recognition methodology, for instance the SIENA approach (Zhu et al., 2021).

In this PASTA prototypical workflow, the considered performances are: adjacent matrix, critical mass, used payload and entertainment FSUs percentage.

Figure 4 shows the results. Both solvers have performed 1'000 generations (Solver 1: randomly 1'000, Solver 2: 10 generations with 100 population each). Generated configurations are reported with their performance values on the y axis and the number of crew on x axis.

Solver 1 has brought 1'000 results and it is possible to analyse alternatives by applying filters. In this case, it wants to skim off configurations with less than 30 people, AdjMtx value above 60, CrtMass under 1.20 and PlUtls 100%. Designers can then compare the outcomes and select the most promising ones.

Solver 2 leverages on genetic algorithm (NSGA-II) and improves configurations generation after generation. The optimisation process' goals lead to pick out configurations with specific performances. This solver has brought much fewer results and because of this, outcomes could be easier to be analysed.

Further development of PASTA could be in its evaluation system. This could be the integration of other performances evaluation and then by assigning a *fitness function* that rates an overall score basing on performances.

In this research, a Spaceship is considered as a complex building system that should provide comfort to its inhabitants. Its internal space has been optimised with the support of generative design to enhance the astronauts' wellness. The proposed workflow can interface with external data (spreadsheet and file). This is a crucial feature that improves the collaborative design since the design of a spaceship requires participation of several disciplines/teams.

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