

Crew-Passenger Ratio Implications on Commercial Spaceflight Design & Survivability: A Discrete Event Simulation Framework

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As the commercial human spaceflight industry begins to take off, an industry-standard ratio of trained staff to paying passengers on-board these trips has yet to materialize. Unlike airlines and cruise ships – where there are well-defined crew-to-passenger ratios that are followed for safety and customer-experience reasons – the cost of commercial spaceflight is not yet scalable due to the limited reusability of launch vehicles. Given that each commercial spaceflight crewmember takes the place of a paying passenger, an appropriate balance in occupant composition is worth identifying. Furthermore, a key factor to consider is the potential for in-flight emergencies and necessary response and recovery times. For example, it can be expected that astronauts or professional crewmembers will have far more training and familiarity with responding to an emergency scenario than regular paying passengers – therefore being able to act faster, perform more accurately, and be in a position to assist others (i.e., improve passenger evacuation performance). The dynamics of this dilemma can be further exacerbated by other factors such as occupant capacity, flight duration, destination, gravity, volume, layout, number of safe havens, time of emergency, and type of emergency. This paper presents a discrete event simulation approach and preliminary framework for evaluating the relationship between crew-to-passenger ratio and evacuation times. The context of a generic, low-earth orbit, commercial spaceflight design reference mission is utilized. The goal of this initial framework is to be able to conduct preliminary feasibility and safety studies of commercial human spaceflight services and ultimately provide a tool for optimizing the appropriate crew-to-passenger ratio with respect to volume and layout.

Nomenclature

<i>CFR</i>	=	Code of Federal Regulations
<i>CSF</i>	=	Commercial Spaceflight
<i>C:P</i>	=	Crew-to-Passenger
<i>C&W</i>	=	Caution & Warning
<i>DES</i>	=	Discrete Event Simulation
<i>FAA</i>	=	Federal Aviation Administration
<i>HW</i>	=	Half-Width
<i>LEO</i>	=	Low-Earth Orbit
<i>SFP</i>	=	Spaceflight Participant
<i>UNIF</i>	=	Uniform Distribution

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I. Introduction

THE growing commercial spaceflight (CSF) industry promises to provide private passengers some extent of the human spaceflight experience. For the near-future, this service has been proposed as brief suborbital flights (e.g., Blue Origin, Virgin Galactic) and short-duration stays in LEO habitats (e.g., Axiom Space). These experiences would involve a handful of sparsely-trained passengers accompanied by a minimal number of crewmembers/trained staff (or none at all). As these experiences increase in duration, so does the risk of an emergency occurring (e.g., fire, depressurization), which threatens the lives of all occupants and/or the continuation of the flight itself.

Given this context, variability in CSF crew-to-passenger ratio is highlighted. For airlines, a generally consistent ratio of crew and passengers is used for safety and comfort reasons. But unlike airlines, the commercial spaceflight industry struggles with scalability due to the limited reusability of vehicles. Thus, the economic impact of flying a staff member rather than a paying passenger is felt more deeply. However, this is a relationship especially worth studying when considering the likelihood of an emergency and the available responses to it. For example, astronauts or professional crewmembers will likely have far more training (in terms of translation in zero-G, understanding of station layout, and mastering the ability to remain calm and collected) and therefore may respond faster and more appropriately than a paying passenger would. Meanwhile, the passengers will likely be minimally trained, not in peak physical fitness condition, easier to become disoriented (in terms of layout and space adaptation), and may fail to grasp the severity of an alarm or emergency event resulting in precious seconds being wasted. Table 1 presents some examples of recent commercial spaceflight profiles based on publicly available information.

Table 1. Profiles of Recent Commercial Spaceflights

Experience	Type	Duration	Training Summary	C:P
Virgin Galactic ⁵	Suborbital	90 min	Pre-flight training program: Several days of preparation with in-house NASA-experienced instructors	2:2
SpaceX Inspiration4 ⁶	Orbital	3 days	Centrifuge training, Dragon simulations, zero-G plane training, altitude chamber training	0:4
Axiom Mission 1 ^{7,8}	Orbital w/ Station Stay	2 weeks	700 - 1000 hours of training involving: safety, health, ISS systems, launch operations, and research & technology payloads	1:3
Blue Origin ⁹	Suborbital	10-11 min	One day (i.e., one day before launch) of training. Involves: mission & vehicle overviews, in-depth safety briefings, and mission simulation and instruction (e.g., operational procedures, communications, and maneuvering in a weightless environment)	0:6
Space Perspective ¹⁰	Suborbital	6 hours	No special training outside of required pre-flight “programs” such as a safety briefing, vehicle walkthrough, and an operations overview of ascent and descent.	1:8

The dynamics of this dilemma vary based on several other key factors (e.g., launch vehicle, crew vehicle capacity, spaceflight duration, destination location, destination volume, destination layout, destination gravity, the routes and number of egress paths at all times, lengths of egress paths, provision and layout of mobility aids, time of emergency, type of emergency, number of emergencies, location of the emergency, quality of caution & warning system, response time in terms of perceiving and comprehending alarms, etc.). For purposes of this paper, scope is limited to a basic, hypothetical commercial space station (and customer experience including flight duration and training fidelity) that is

⁵ <https://brochure.virgingalactic.com/preflight/>

⁶ <https://www.nasaspacesflight.com/2021/08/inspiration-4-update/>

⁷ <https://www.axiomspace.com/news/ax1-15-facts>

⁸ <https://www.axiomspace.com/news/ax-1-crew-undocks-from-iss-axiom-astronauts-begin-journey-home>

⁹ <https://www.blueorigin.com/new-shepard/become-an-astronaut>

¹⁰ <https://spaceperspective.com/faq>

most likely to resemble a real, near-future commercial spaceflight. More specifically, this study considers the respective evacuation times for crew and passengers within a single, medium-sized inflatable module docked with a single escape vehicle. Working assumptions are discussed in Section 3 and key driving variables are listed in Table 2.

Table 2. Key Variables Defining the Study Scope

Variable	Type(s)	Considerations
Entities	<ul style="list-style-type: none"> • Crew (i.e., experts) • Passengers (i.e., novices) 	<ul style="list-style-type: none"> • How many of each? • What is the optimal ratio given a specific habitat design and/or mission scenario?
Resources	<ul style="list-style-type: none"> • Escape vehicles (e.g., Crew Dragon) • Modules (e.g., crew quarters) • Passageways/corridors 	<ul style="list-style-type: none"> • How many escape vehicles? • What is the station layout? • Are there non-capsule safe-havens?
Activities	<ul style="list-style-type: none"> • Evacuation (i.e., starting at detection of a fire event and ending at complete occupant egress) 	<ul style="list-style-type: none"> • Differences in task performance between crew and passengers • Crew could help passengers evacuate faster once they encounter each other
Controls	<ul style="list-style-type: none"> • Evacuation strategies, rules, protocols, etc. 	<ul style="list-style-type: none"> • E.g., all members are supposed to evacuate using one Crew Dragon

The theory behind this study is that the presence of trained crewmembers (and interaction with them) decreases the evacuation times of passengers. However, due to its complexity, this unique occupant interaction will be modeled and studied in forward work. Nevertheless, it is believed that there is a “sweet spot” regarding the crew-to-passenger ratio that will lead to the most optimal evacuation times for all occupants. This study aims to provide a framework to begin understanding respective CSF occupant evacuation times within a basic, hypothetical design reference mission. It is expected that such a preliminary simulation model will be able to consistently and accurately produce results supporting the hypothesis that crew will always evacuate faster than passengers.

II. Background

For commercial human spaceflight to be successful, it is imperative to win the trust of potential customers by maximizing occupant safety. Therefore, safety training and protocols for emergency situations must be well-established. For instance, Reference 1 conducts a preliminary experiment to study how suborbital spaceflight participants (SFPs) return to assigned seating during an emergency scenario. One finding suggests that each SFP may use their own unique approach to perform the same task, which can result in unpredictable events. Thus, the importance of developing thorough training protocols and incorporating human-centered design is stressed.

Therefore, it is imperative to understand sequence of events and expected occupant behaviors. In this paper, the simulation study commences at the start of occupant response to a fire emergency. That is, it is assumed that all occupants have successfully perceived and comprehended the emergency. The Federal Aviation Administration (FAA) suggests that in small habitable volumes (such as the hypothetical space station referenced in this paper’s simulation), “human senses may suffice to detect a fire event.”² Moving along the response process (particularly within a professional astronaut mission), “evacuation is executed only if absolutely necessary” after all other resources for mitigating/eliminating the fire(s) are exhausted.³ However, when minimally-trained passengers are introduced into the scenario (particularly in small habitable volumes) it is recommended that “total evacuation [be established] as the default emergency response” due to: a lack of alternative on-board safe havens, a lack of ability to isolate habitat sections, and the rapid loss of available oxygen.³ Furthermore, corridors that lead to docked crew capsules (as seen in this paper’s hypothetical space station) should remain clear of obstructions and unnecessary activity as occupants “never want to be cut off from their escape vehicle.”⁴

As in any other evacuation context (e.g., terrestrial buildings, cruise ships, commercial airplanes, etc.), Reference 5 notes that there are specific types of data that are sought after when studying evacuations and developing a model: delay times, movement/translation speeds, occupant characteristics (differences in actions, reactions, and capabilities),

actions during evacuation (errors, poor decisions, etc.), effects of obstructions in travel paths, and egress/exit choice decisions. It points out that such aspects are easily neglected out focusing only on egress times. Despite this important observation however, this paper intentionally focuses on evacuation times in order to refine fundamental aspects of the framework, which may later be used for more complex studies examining occupant interactions, for example.

Regarding human interactions and behavior relevant to the scope of this paper, Reference 6 validates the natural response of “fleeing from dangerous events such as fires” as being the “sensible thing to do.” However, it notes that the crowds involved are not always necessarily “panicked or irrational.”⁶ That is, perhaps the layman’s performance in response to an emergency is underestimated as being close to useless. Although competitive behavior may emerge during these events, social bonds and empathy for others remain intact.⁶ Furthermore, even in the midst of an escalating emergency and numerous casualties, the Beverly Hills Supper Club Fire of 1977 showed that “staff continued to look after customers, with waiters attending to the safety of those at their assigned tables.”⁶ Similarly within the airline context, it was found that flight attendant interaction with passengers during an evacuation resulted in substantially efficient outcomes and low evacuation times.⁷ Thus supporting the expectation for (and efficacy of) staff interaction.

With the understanding that non-staff occupants may be capable of initially helping themselves to some extent, the importance of information sharing is emphasized. Reference 6 points out that “the single biggest killer in emergencies is lack of information,” such as not fully realizing the danger and necessity for prompt evacuation. Another example is a lack of knowledge on a structure’s internal connectivity (layout), specifically in new, large, and complex spaces.⁸ Despite some level of self-reliance among non-staff occupants, eventually the effects of stress (from environmental complexity, dynamically changing situations, time pressure, etc.), diminished sensory functioning, reduction of awareness, and increase in disorientation begin to set in and affect decision-making capabilities.⁸ Unfortunately, as will be the case for many CSF services, the minimal training provided to customers (relative to that of an astronaut or staff member) may not be sufficient to avoid the aforementioned familiarization risks. This is precisely when individuals trained for these situations are able to significantly impact the survival of all occupants.

Real-world (non-simulated) evacuation data is extremely limited.⁷ Moreover, literature on emergency passenger evacuation is heavily aviation-based. Nevertheless, much can be gleaned from similar studies in commercial airplane contexts. In fact, it is claimed that simulation tools are more valuable to the aviation industry than evacuation drills.⁹ Even with just a rudimentary conceptual model (flowchart), several parameters and evacuation strategies can begin to be adjusted to provide more realistic results. That is, computer-based simulations are valuable in describing human behavior, describing interaction with the environment, and predicting the total time of evacuation. With respect to the latter, Title 48 Code of Federal Regulations (CFR) Part 121.291 requires passengers to evacuate from an aircraft within 90 seconds. This requirement was used in Reference 7 to develop a foundational model/framework that accurately results in near-realistic airplane evacuation times, from which future studies that consider human behaviors, actions, and interactions can be examined. Unlike the aviation industry, however, there is no federal regulation limit on spaceflight evacuation times, not only further adding to the complexity of variables to consider but also highlighting the nascent nature, the need for additional research, and the value of analytical methods within this topic.

III. Methodology

The overarching goal of this research effort is (1) to propose a simulation framework as tool for making more informed decisions on habitat design, layout, and operational strategies, and (2) to investigate the effects of crew-to-passenger ratios on occupants’ safety during emergency evacuations. In this study, the Arena simulation modeling software package is used for implementing the preliminary simulation framework. This flowchart-based capability allows for model development, definition of simulation parameters, running discrete event simulations, and generation of reports that allow for understanding and exploration of varying scenario conditions. The following subsections address key considerations for the implementation of the preliminary simulation framework.

A. Assumptions

Due to the numerous factors and variables that play influential roles within the context of this study, it was necessary to establish a series of working assumptions for the hypothetical commercial spaceflight being referenced. It is important to emphasize that although many of these factors would typically deserve detailed consideration (e.g., exact habitable volume, diameters, lengths, mobility aid layout, C&W system design, indicators, labels, etc.), these factors are not the focus of this study. Rather, general assumptions are made to allow for complete focus on the feasibility of such an initial simulation tool. Thus, the following assumptions of Design, Events, and Processing (flow of occupants) were utilized to scope/inform the development of the preliminary simulation framework:

- Design:
 - a) A LEO station comprised of one single module, which is divided into forward and aft sections
 - b) A module-long corridor runs through the center, and it is divided into forward and aft passageways
 - c) The forward and aft passageways are separated by a hatch
 - d) To enter either passageway from a section, occupants pass through a section-passageway hatch
 - e) One crew capsule (escape vehicle) is docked to the forward end the forward passageway
 - f) Both the station and the escape vehicle have an occupant capacity of seven.
 - g) C:P ratio of 1:3 reflects realistic business/economical expectations.
 - h) Figure 1 is a visual representation of this hypothetical space station
 - i) Figure 2 highlights the sections, hatches, and crewmembers

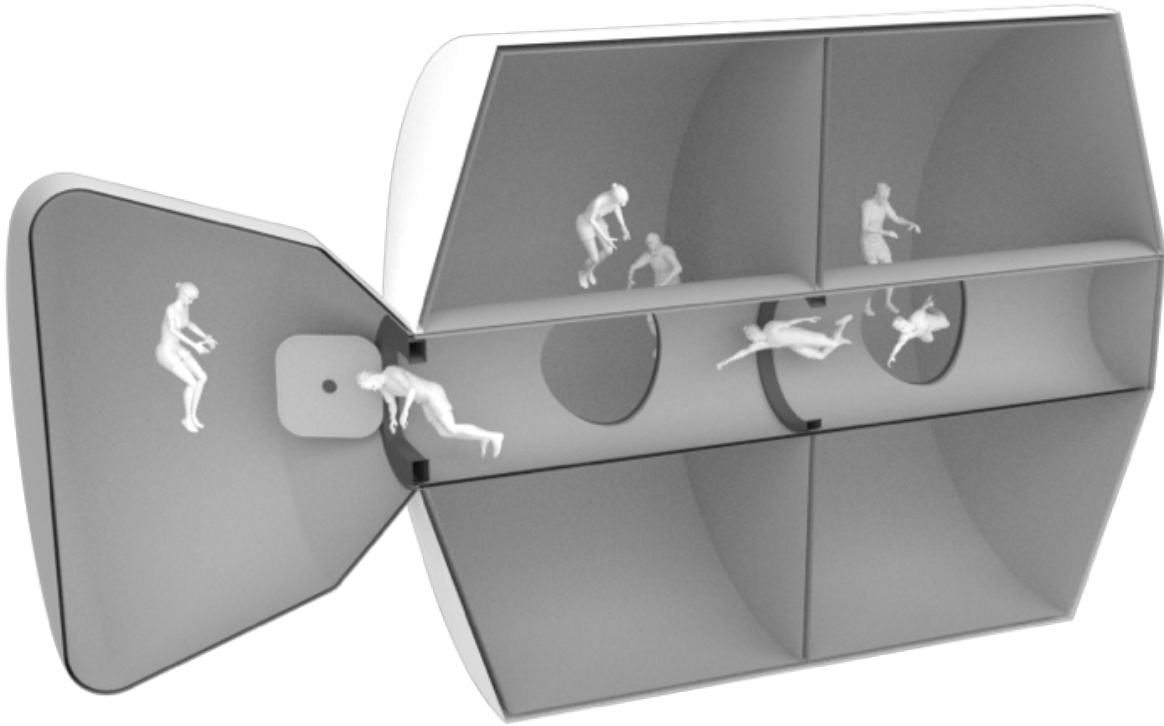


Figure 1. Hypothetical space station referenced in this study

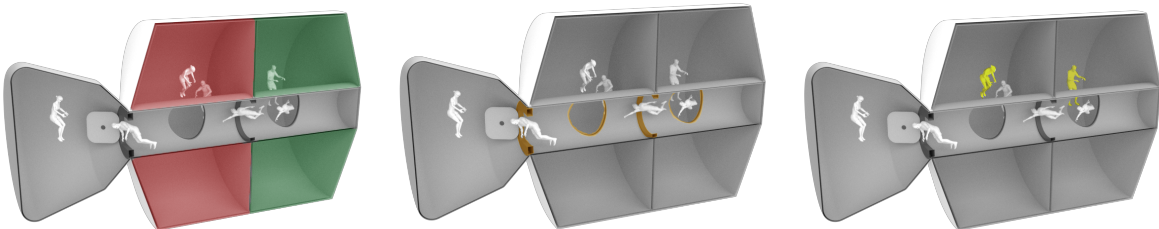


Figure 2. Sections (left), hatches (middle), and crewmembers (right) referenced in this study

- Events:
 - Occupants are encouraged to move around the station in a distributed fashion for safety reasons
 - A fire emergency occurs somewhere in the station that requires total evacuation of all occupants
 - All occupants are within a section (not the corridor) when the fire starts
 - The simulation begins once occupants start to exit either section (i.e., Forward, Aft).
 - Figure 3 demonstrates evacuation flow from sections, through hatches & passageways, to vehicle

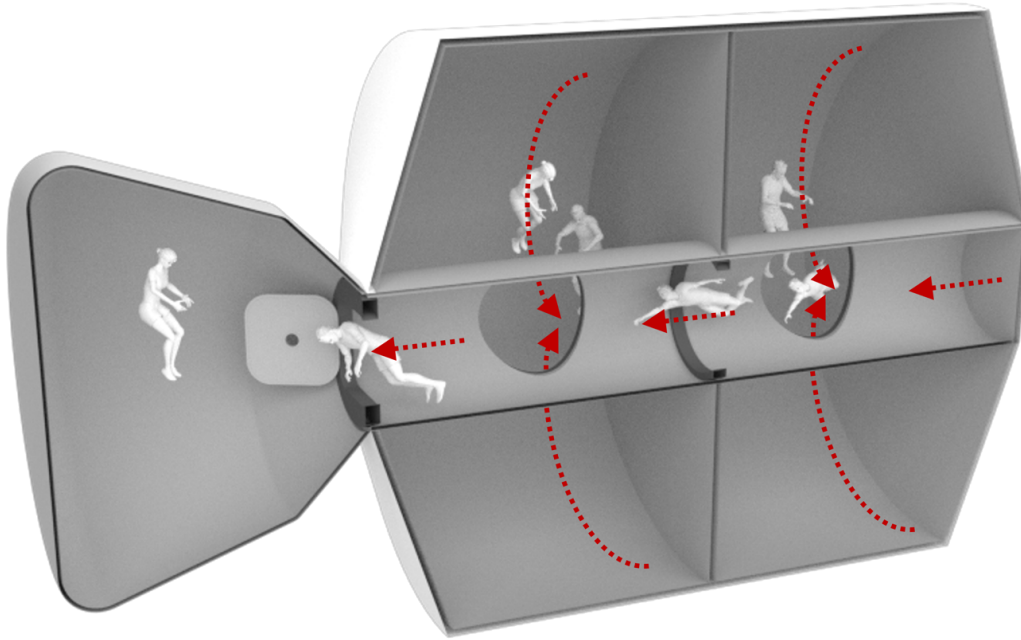


Figure 3. Visual representation of evacuation flow

- Processing
 - Sections can hold up to 3 occupants/time; 1 occupant must be a crewmember
 - All hatches can process 1 occupant/time
 - Corridor halves (passageways) can process 4 occupants/time (implying the existence of queues)
 - Due to input constraints in Arena, occupant speed is actually entered as corresponding evacuation time. Since real data on crew and passenger evacuation times does not yet exist in the CSF context, it is recommended to use a uniform distribution (based on educated estimate) for this preliminary simulation framework.¹⁰ Table 3 lists these uniform distribution values for each evacuation process. The evacuation times are uniformly distributed between the minimum and maximum values in seconds (e.g., UNIF(1,3) refers to a uniform distribution between 1 to 3 seconds).

Table 3. Crew and Passenger Evacuation Time Distributions (s)

	Section to Passage	Translate through Passage	Passage to Passage	Passage to Vehicle
Crew	UNIF(1,3)	UNIF(3,6)	UNIF(1,3)	UNIF(2,5)
Passenger	UNIF(2,4)	UNIF(4,8)	UNIF(2,4)	UNIF(3,8)

B. Constraints

Together with the established assumptions, the following model constraints were identified and utilized to further scope the scenario, inform initial models, and proceed with studying the preliminary simulation framework:

- Arrival:
 - All occupants have a 50% chance of “starting” in either Forward or Aft sections.
- Entity Types:
 - Occupant: Crew (trained, typically fast, well-oriented)
 - Occupant: Passenger (minimally-trained, typically slow, disoriented)
- Processes:
 - Process (a): 1 occupant/time (moving through hatches between sections and passageways)
 - Process (b): 4 occupant/time (moving through passageways)
 - Process (c): 1 occupant/time (moving through hatch between the passageways)
 - Process (d): 1 occupant/time (moving through hatch between the passageway & escape vehicle)
- Queues:
 - Queue at the hatch between sections and passageways
 - Queue at the hatch between the passageways
 - Queue at the hatch between the passageway and escape vehicle
- Performance Measures:
 - The total time it takes for all crew members to complete the evacuation
 - The total time it takes for all passengers to complete the evacuation

C. Conceptual and Computational Models

With the established assumptions and constraints, a conceptual model was developed to allow initial layout of model components and further understand model dynamics and entity/occupant flow. In this representation, occupants move in a simple fashion: they start their evacuation processes from either the forward section or aft section, and proceeds as depicted in Figure 4.

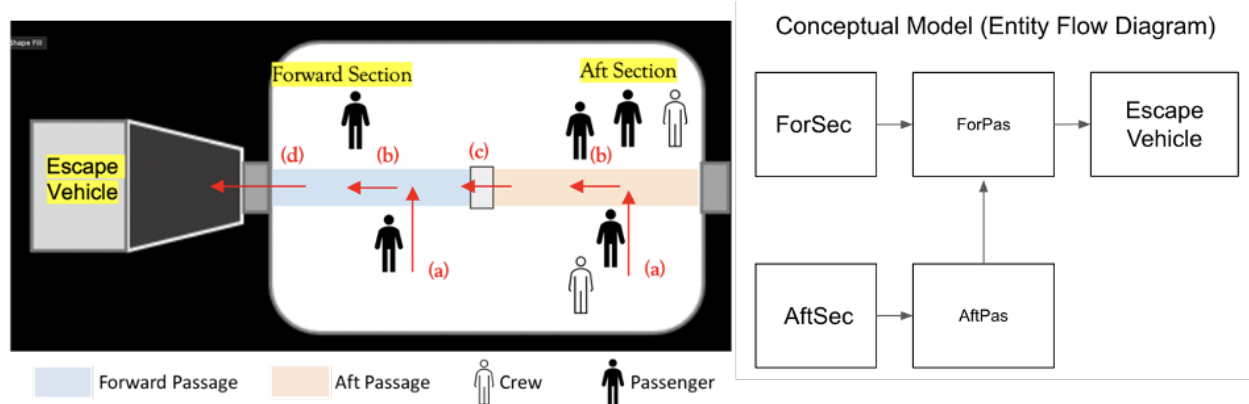


Figure 4. Conceptual model of the preliminary framework

Based on this conceptual model, the Arena simulation modeling software was used to develop a computational model of the preliminary simulation framework. This model allowed for the incorporation of key assumptions, constraints, variables, and operating logic. Figure 5 shows the final iteration of the computation model, which was used to begin recording simulation runs and resulting data.

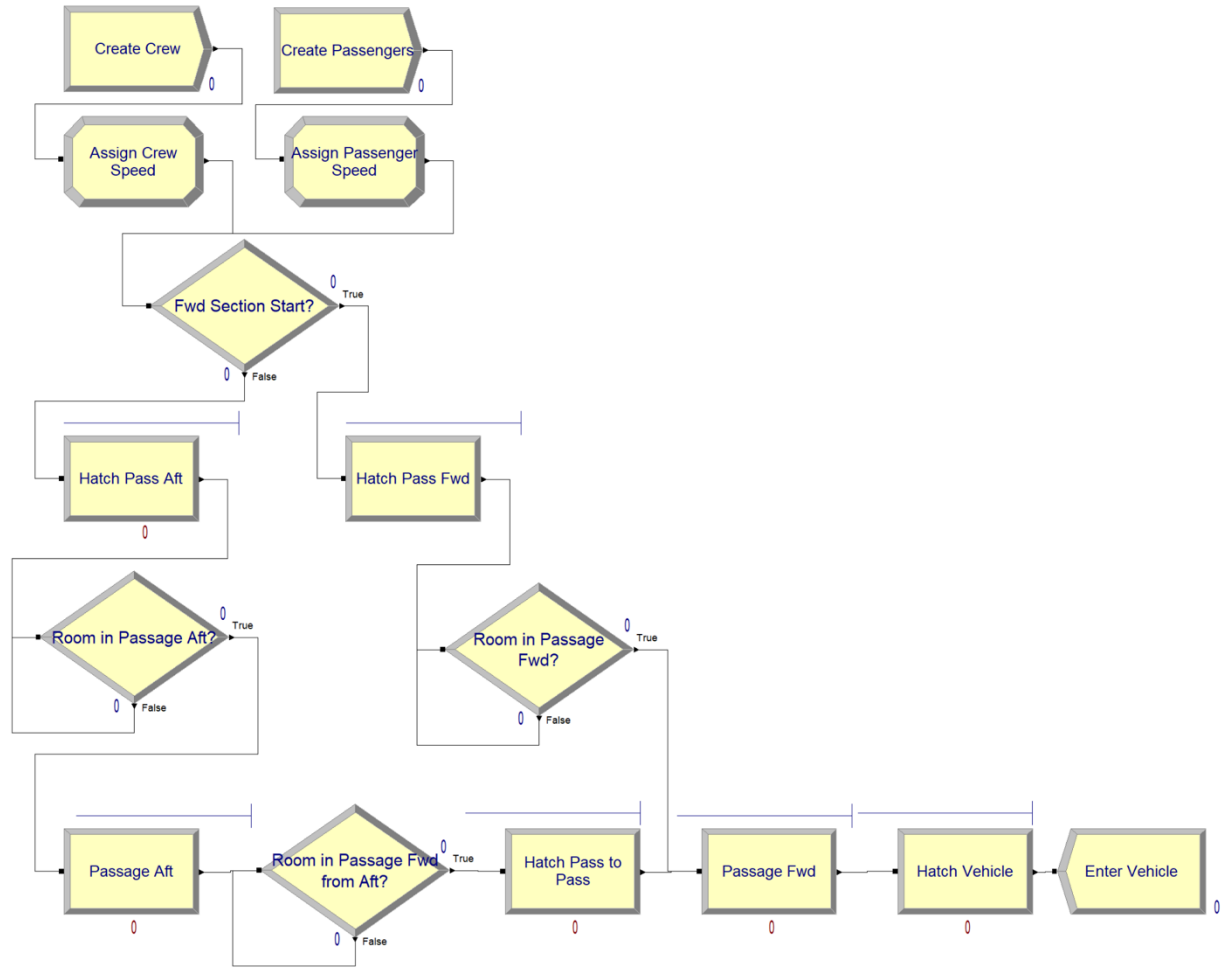


Figure 5. Computational model of the preliminary framework

Each simulation run requires three pre-processes: (1) generating entities/occupants, (2) assigning the distribution of evacuation time to each type of entity, and (3) determining the starting section of each entity/occupant. In generating entities (i.e., seven occupants), crew-to-passenger ratio could be changed manually (e.g., two crew members and five passengers). In assigning the distribution of evacuation time to each entity type, the “translation speed” for crew and passengers are respectively determined. In determining the starting section of each entity, all occupants are individually given a 50% chance of being located in either the forward or aft sections at the time of fire-breakout. Once this last pre-process is complete, the simulation begins (i.e., $t = 0$).

First, each entity passes through the hatch between the section (in which they start) and the corresponding passageway/passage. Then, the entity checks if it can actually enter the passage (i.e., if occupancy limit is not reached, in which case the entity would have to wait and would create a queue). If the corresponding passage can accommodate the entity, the entity proceeds into the passage. While the first entity in either the forward or aft section is performing a transition, others in the same section wait for the completion of the transition. Once the entity enters their corresponding passage (i.e., the forward or aft passage), it starts to head towards the next hatch; four entities could move simultaneously in the same passage as mentioned in the assumptions. In the case where the entity departs from the aft section, the entity needs to proceed with an additional process, that is a transition from the aft passage to the forward passage through a hatch. Again, in order to actually proceed, the entity must check for capacity availability. Once the entity finally reaches the vehicle hatch, it ingresses the escape vehicle, which is the final process in the evacuation. Once all entities complete the evacuation process, the simulation ends.

D. Verification & Validation

For verification of the framework, an initial analysis (next subsection) was performed to confirm whether the simulation model behaves as intended (i.e., that the conceptual and computational models agree with each other). More specifically, it is expected that the crew will always evacuate faster than the passengers (i.e., faster evacuation time of the crew). Validation of the framework, however, is currently out of scope due to the lack of real-life evacuation data on CSFs. Thus, forward work should collect and incorporate real flight data when available and update entity (evacuation) time distributions so as to refine the fidelity and utility of this framework.

E. Initial Analysis

The initial simulation study was performed with three separate crew-to-passenger ratio conditions: (1) one crew member with six passengers, (2) two crew members with five passengers, and (3) three crew members with four passengers. 1,000 replications were run for each case.

IV. Results

Table 4 presents the results of the initial simulation study. The half-width shows the 95% confidence interval on the expected average value. Results show faster total evacuation time for crew regardless of the C:P ratio conditions, supporting our original hypothesis. Interestingly, as the number of passengers decrease among these ratio conditions, a trend appears to emerge: longer total evacuation time and wait time for crew, and shorter time values for passengers. It should be noted that statistical analysis was not performed to confirm this trend but could be conducted once additional simulation features are implemented in this preliminary framework, which is discussed in the next section.

Table 4. Initial Simulation Results of Total Time (C=Crew, P=Passenger, HW=Half Width)

		Total Evacuation Time [s]				Wait Time [s]			
	Entity Type	Avg.	HW	Min. Avg	Max. Avg	Avg.	HW	Min. Avg	Max. Avg
Ratio 1 C: 1 P: 6	C	16.1	<0.42	6.49	34.5	2.74	<0.23	0.00	16.4
	P	31.1	<0.17	22.9	42.4	12.1	<0.16	5.90	20.8
Ratio 2 C: 2 P: 5	C	16.7	<0.33	8.95	36.2	3.41	<0.21	0.00	18.7
	P	30.8	<0.17	22.6	41.5	11.7	<0.16	5.08	20.7
Ratio 3 C: 3 P: 4	C	17.5	<0.27	10.2	35.0	4.23	<0.18	0.345	18.1
	P	30.6	<0.19	20.6	42.2	11.5	<0.18	5.01	21.4

V. Discussion

The developed simulation model consistently produced results showing that crew will always evacuate faster than passengers, which is in accordance with the expected behavior. Therefore, the bare minimum simulation capability was confirmed, and higher fidelity simulation models should build upon the framework presented in this paper. This section discusses avenues for forward work and the expected benefits of this proposed simulation tool for practitioners, including space architects, engineers, and CSF service providers.

A. Forward Work

This preliminary simulation framework does not consider any crew-to-passenger interactions during the evacuation process (i.e., presence of one entity type does not effect the performance of the other in this initial model). In reality however, it is expected that passengers could directly benefit from the presence of crew; that is once a passenger encounters a crewmember during evacuation, the crewmember is likely to provide some form of evacuation guidance or direction that would facilitate (i.e., expedite) the passenger's evacuation process. The implementation of

such a crew-to-passenger interaction could be done in the Arena simulation software by assigning a new/faster Passenger Time Distributions once the condition is met for that passenger (i.e., encounters a crewmember).

Future work could also improve on simulation capabilities to allow users to test a wide spectrum of CSF scenarios/case studies. The current simulation assumes a hypothetical habitat consisting of forward and aft sections, and straightforward passageways with no other detail included (e.g., galley area, crew quarters,); it fails to consider/test variants of such parameters (e.g., the number of sections and types of internal layout). Additionally, the presented simulation study treated the two sections as identical functional areas; however, it is expected that CSF habitats could consist of different types of functional areas, including private and public spaces. Therefore, forward work should explore and consider a broad range of space architecture designs and CSF operations/activities.

Another potential avenue for future work includes implementing passenger error during evacuation. There could be a scenario where a passenger could make a poor decision on the evacuation route and/or head to the wrong way. Such a behavior could be implemented by introducing failure rates of the passengers' evacuation processes; it could be assumed that more complicated interior design and layout could increase the failure rates. Furthermore, even though it was assumed that all occupants initiated the evacuation process immediately after the fire event occurred in the presented simulation study, variance in this behavior may be observed in a real-world scenario (i.e., inconsistent recognition of emergencies among crew and passengers).

B. Utility

This proposed preliminary simulation framework could be improved by implementing the above-mentioned forward work features. It is designed with the intention to help make more human-centered informed decisions on habitat interior design, layout, configuration, and operational strategies – even as simple as doubling partitions to consider a four-section volume rather than one with two larger sections (Figure 6).

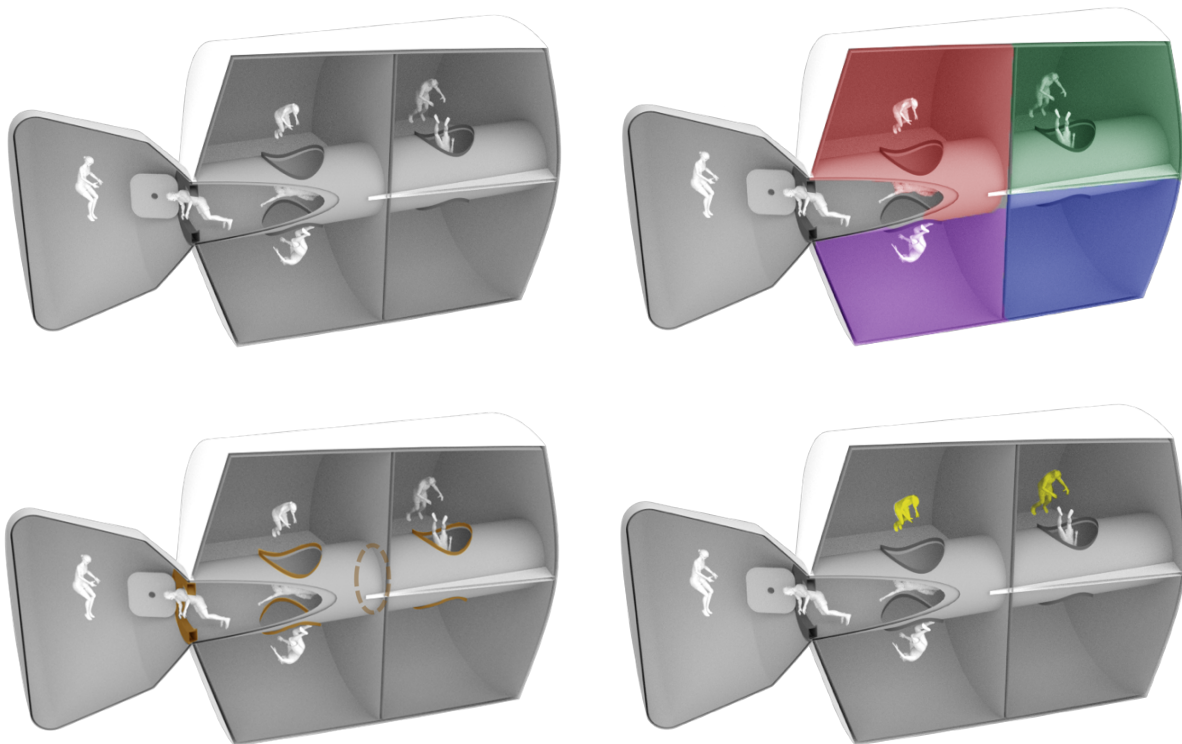


Figure 6. Four-section version of the hypothetical space station

It is expected that the utility of this simulation tool will be more pronounced in application with complex space habitat design – the habitat and escape vehicle configuration must be well considered to ensure the emergency evacuation success¹¹. Habitats designed scalability in mind could largely benefit to investigate in advance the egress effects of the additional modules, vehicles, layouts, zoning strategies, anticipated flow, capacities, safe havens, etc.

CSF companies could also benefit from the proposed simulation tool to make more informed decisions on their operational planning. For example, variance in passenger evacuation capabilities could result in unexpected passenger behavior, a risk that CSF companies may want to minimize by providing passengers well-established training protocols. Noting additional costs for such training, CSF companies may benefit from identifying: (1) a C:P “sweet spot,” (2) the corresponding required levels of training, and (3) habitat and escape vehicle configurations, including the number of the docked escape vehicles. Of course, several other influencing factors could interplay, requiring a comprehensive analysis of these trades. But this proposed simulation model could help provide an initial cost-effective insight to operational options and their feasibility.

VI. Conclusion

CSF service providers will at some point (for safety and/or economic reasons) face the challenge of determining the appropriate balance between staff and passengers onboard their flights. This study provides a preliminary simulation framework for investigating crew-to-passenger ratio effects on total evacuation time during CSF emergency scenarios. This preliminary simulation model is developed under a set of general DRM assumptions using the Arena simulation modeling software package. This model consistently produces results showing shorter evacuation times for crew as compared to passengers, which verifies the bare minimum simulation capability. With this preliminary simulation model as an initial reference, future iterations can incorporate real flight data while also expanding model capability to account for more of the associated variables, assumptions, and constraints (e.g., occupant interactions, variance in occupant behaviors/errors, different station designs/layouts, etc.). This simulation framework is intended to serve as a stepping-stone toward developing a computational tool that can inform conops refinement, requirements generation, task analyses, trade studies, safety assessments, business models, and more.

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