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Discrete event simulation of long-duration space station operations for rapid evaluation

Kun-Peng Lin *, Meng-Li Wang, Yuan Hong, Yang Yang, Jia-Xin Zhou

Beijing Satellite Navigation Center, Beijing 100094, China

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A B S T R A C T

A long term space station operational scenario involves a large number of on-orbit missions, however, for their successful implementation they require various logistics missions to be performed. Logistics missions are triggered by on-orbit missions and there are complex interactions between different missions. Based on the computational efficiency afforded by event-based simulation, Discrete Event Simulation (DES) is used to model diverse on-orbit and logistics missions holistically within an integrated scenario and schematize it as a discrete system. It helps to quickly evaluate the physical feasibility and performance effectiveness of complex space station operations. Moreover, operational uncertainty is introduced into the DES model, comprising launch delays of visiting vehicles and onboard emergencies hazarding the safeties of space station or astronauts. Monte Carlo simulation is adopted to help in stochastic analyses and five measurable metrics are further defined to quantify the impact of uncertainty on nominal scenarios. The proposed DES model and associated metrics are demonstrated with both nominal and contingency operations. Simulation results indicate that such an approach is effective and efficient in simulating space station operations and able to support the top-level mission design of China's future space station program.

1. Introduction

The United States of America and Russia have successfully built and operated several space stations such as the International Space Station (ISS) and the Mir. In a typical long-duration space station scenario, various on-orbit missions are required to be performed simultaneously, incorporating many aspects such as crew life support, experiments, utilization arrangements, maintenance of platform and payload, as well as orbital maneuvers. Meanwhile, the logistics missions, namely the visits of the cargo vehicles and the manned vehicles, are scheduled and executed on Earth to enable the resource resupply and the crew rotation. The logistics missions are triggered by the on-orbit missions, and different operational missions are coupled with each other. Therefore, the diverse operational missions should be designed and planned together, which is necessary to improve the utilization capability and minimize the operational cost of the life-cycle, to make the space station program feasible and affordable.

China has been engaged in a massive manned spaceflight project and intends to operate its own space station by the year 2020, which paves the way for long-duration expansion by Chinese astronauts in outer space [1]. Based on this background, the authors of this paper have recently investigated the optimization of the space station's orbit [2], the space station orbital mission planning under multi-constraints [3], the space station logistics strategies [4], and the overall mission planning for the space station in order to optimize the total on-orbit time of the crew and upload utilization mass, while minimizing the propellant consumption and total number of visiting vehicles [5]. The optimization approaches in [2–5] allow an elegant and compact formulation for planning space station operational missions. It should be noted that a major limitation in these previous investigations is that the uncertainties in the mission operations are not considered, such as the delay of the visiting vehicles and other on-orbit emergency events that may cause safety issues.

On the contrary, simulation models characterized by incorporating the randomness are able to quantify the uncertainties in the operational process. The discrete event simulation (DES) can avoid potentially large time steps, and a high computational efficiency can be achieved, therefore DES has become a popular tool for analyzing the large-scale systems. DES has been widely employed in the sectors of berth planning and logistic resource optimization [6], future reusable launch vehicles [7], air traffic flow [8], aerospace

* Corresponding author.
E-mail address: linkunpeng@126.com (K.-P. Lin).

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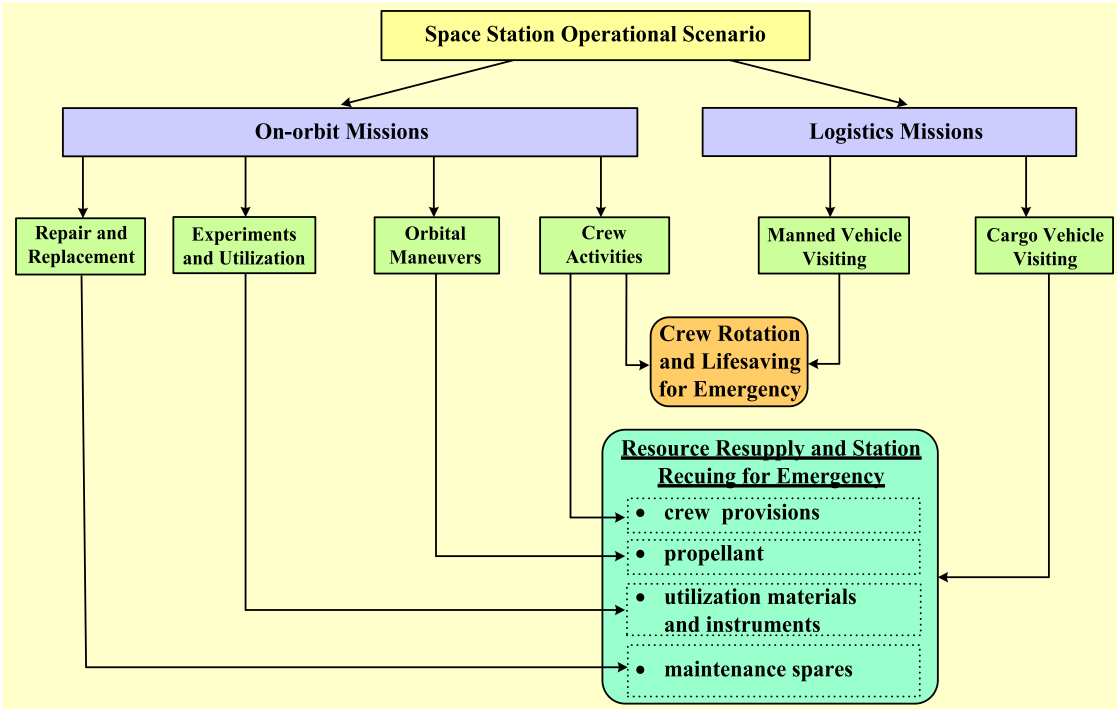

Fig. 1. Description of space station operational scenario.

vehicle maintenance and logistics process [9] and facilitated modeling [10].

With respect to the simulation of the space station operations, de Weck et al. [11] developed a software tool named *SpaceNet* based on the DES method to provide effective analyses of ISS resupply strategies [12,13], and Cates [14] investigated a DES model to assist the evaluation of the viability of completing the assembly of the ISS by NASA [15,16]. Nevertheless, *SpaceNet* did not incorporate stochastic analysis of probabilistic events in its current version and could not perform the uncertainty analyses for the space station operations [11]; the studies performed in [14–16] mainly focused on the modeling of the launch processes of space shuttles, however, the triggering interactions between the on-orbit and logistics missions are not considered.

This study aims to develop a DES approach to evaluate the space station operational scenarios with the stochastic analyses together with the interactions of multiple operational missions considered. The new approach offers an effective alternative to physical experimentation for mission designers to conduct experiments and make predictions prior to the execution of space station operations [17]. Thus, it helps to test the different operational strategies of input designs for rapid evaluation of physical feasibility and performance effectiveness.

Firstly, DES is employed to schematize the space station operational scenario as a discrete system, wherein the events include both the on-orbit and logistics missions, and the objects consist of the spacecraft (space station, cargo vehicles and manned vehicles) and supplies (crew provisions, utilization materials and instruments, maintenance spares, and propellant). The characteristics of the objects are used to describe the system state of a space station operational scenario, which is affected by the events occurring at discrete points. The changes of system state caused by events sequentially push the forward of DES. Then, object-oriented methodology is used to abstract the classes of both system state and events. Furthermore, Monte Carlo simulation is adopted to determine the stochastic impacts of the launch delays and onboard emergences on nominal scenarios. Finally, based on the Monte Carlo simulations, five measurable metrics are defined in order to quantify the impacts of the stochastic aspects.

The proposed DES model and the associated metrics are applied to the notional long-duration operational scenarios of China's future space station, and rapid evaluation on both normal and contingency operations is demonstrated. In addition, the effects on the on-orbit missions and completion of operational scenarios as a result of launch delays of cargo vehicles and manned vehicles, as well as the frequencies of onboard emergencies are analyzed. The results indicate that this study can be of practical relevance for mission design of space station operations.

2. Space station operational scenario simulation

The initial flights in the "build-up phase" of the space station deliver large infrastructure elements such as the habitats, the solar arrays, the racks, and the orbital replacement units along with supply items and crew members. As the amount of the infrastructure and the supplies grow, the space station enters the "sustainment phase" wherein on-orbit utilization of increasing duration is enabled to lead up to continuous human presence [12]. Two major categories of missions in a long-duration space station operational scenario are depicted in Fig. 1 [4]. On-orbit missions are executed aboard the station, including repair and replacement of the systems, experiments and utilization, orbital maneuvers, and crew activities, all of which consume onboard resources, such as maintenance spares, utilization materials and instruments, propellant, and crew provisions.

The onboard duration of crew is strictly constrained due to physiological and psychological health issues. Moreover, on-orbit resources are stored in a limited amount. Therefore, on-Earth logistics missions need to be performed in order to resupply resources and fulfill crew shifts through cargo vehicles and manned vehicles. However, on-board emergencies usually caused by the critical failure systems, such as environmental control system, life support system, power and thermal control system, may threaten the safe operation of space station. At the same time, members of the crew

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may spontaneously become sick. In these cases, immediate visits of cargo or manned vehicles are required to provide necessary assistances.

When any onboard resource approaches its minimum acceptable level and the time of astronauts onboard approaches the rotation period, a resource resupply and a crew shift need to be performed. The minimum required quantity of resources and the crew rotation period enable admissible time intervals for resource resupply and crew rotation, respectively. The launch times of cargo vehicles are first required to fulfill the onboard resource consumption, also the launch times of manned vehicles are first required to fulfill the crew rotation. Furthermore, the launch times have to satisfy the constraints of launch window [3]. However, launch delay might occur due to uncertainties, such as inclement weather, prolonged preparations by added work, personnel or infrastructure problems [16].

The DES model of space station operations can be described in terms of both events occurring and system state changed at discrete points in time. Here, events include both the on-orbit and logistics missions, which produce changes to state variables or trigger other events. Accordingly, the DES of a space station operational scenario is abstracted to comprising ten main types of events: Repair and Replacement, Experiment and Utilization, Orbital Maneuver, Crew Activity, Visit of Cargo Vehicle, Visit of Manned Vehicle, Launch Delay of Cargo Vehicle, Launch Delay of Manned Vehicle, Emergency Endangering Station and Emergency Endangering Crew. Thus, the system state within the simulation is mainly defined by the masses of onboard resources, crew size, whether the onboard emergencies happen, whether the station executes maneuvers (for the arrangements of experiments and utilization, such as microgravity experiments, are restricted to orbital maneuvers [18]).

Additionally, the stochastic inputs for the DES include probabilities of contingency events such as launch delays and onboard emergencies, and probability distributions for the possible duration used to prepare the following launch if delays occur. Hence, the DES of space station operational scenario helps to review how the delays of resource supplies and crew rotation affect the on-orbit missions (e.g., experiments, maintenance, and crew working) and to analyze the frequencies of onboard emergencies within a long-duration scenario.

3. Discrete event simulation model

3.1. Classes of events

Among the ten main types of events, the attributes of some are similar to others, thus, they are classified into three major classes: On-orbit Event, Launch Event and Contingency, in order to describe the attributes more conveniently. The object-oriented methodology is employed to abstract the classes of both the events and the system state.

The class of On-orbit Event includes Repair and Replacement, Experiment and Utilization, Orbital Maneuver and Crew Activity, the characteristics of which are presented in Eq. (1),

$$\begin{aligned} \textit{On-orbitE} = \{ & id, name, type, startTime, duration, endTime, \\ & mSpareConsumed, mUtilizationConsumed, \\ & mPropellantConsumed, \\ & mCrewProvisionConsumed\} \end{aligned} \tag{1}$$

where *id* is the unique number to distinguish from other events; *name* describes the meaning of the event; *type* denotes the type of the event; *startTime* and *endTime* represent the time when the event occurs and ends, respectively; *mSpareConsumed*, *mUtilizationConsumed*, *mPropellantConsumed* and *mCrewProvisionConsumed* are the consumed masses of the maintenance spares, utilization materials and instruments, propellant, and crew provisions, respectively.

The class of Launch Event combines Visit of Cargo Vehicle and Visit of Manned Vehicle, the characteristics of which are expressed in Eq. (2),

$$\begin{aligned} LaunchE = \{ & id, name, type, launchTime, mSpareUpload, \\ & mUtilizationUpload, mPropellantUpload, \\ & mCrewProvisionUpload, nCrewUpload\} \end{aligned} \tag{2}$$

where *id* is the identification number of the event; *name* describes the meaning of the event; *type* denotes the type of the event; *launchTime* represents the time when the vehicle is launched; *mSpareUpload*, *mUtilizationUpload*, *mPropellantUpload* and *mCrewProvisionUpload* mean the masses of the resources resupplied; *nCrewUpload* represents the number of the crew transported.

The class of Contingency Event encompasses Launch Delay of Cargo Vehicle, Launch Delay of Manned Vehicle, Emergency Endangering Station and Emergency Endangering Crew, the characteristics of which are written in Eq. (3),

$$ContingencyE = \{id, name, type, occurTime, Probability\} \tag{3}$$

where *id* is the identification number of the event; *name* describes the meaning of the event; *type* is the type of the event;; *occurTime* denotes the time when the event occurs; *Probability* means the probability of the event.

3.2. Classes of system state

In the simulations to be performed, the system state of a space station long-duration operational scenario is composed of all the characteristics of objects, and can be described by nine elements, which can be described in the following expression,

$$\begin{aligned} StationState = \{ & mSpare, mUtilization, mPropellant, \\ & mCrewProvision, nCrew, dManned, \\ & bStationEmergency, bManEmergency, \\ & bManeuver\} \end{aligned} \tag{4}$$

where *mSpare*, *mUtilization*, *mPropellant* and *mCrewProvision* are the masses of the resources stored; *nCrew* represents the number of the crew; *dManned* is the duration of the space station staffed; *bStationEmergency* and *bManEmergency* represent whether any onboard emergencies that threaten the space station and the astronauts occur, respectively; *bManeuver* represents whether the space station executes any maneuvers.

3.3. Stochastic models

In the simulations to be performed, for each launch of cargo vehicle and manned vehicle, the events of Launch Delay of Cargo Vehicle and Launch Delay of Manned Vehicle, are modeled as accidental events with small probabilities; similarly, for each space station operational day, the events of Emergency Endangering Station and Emergency Endangering Crew, are also modeled as accidental events with small random probabilities. The probabilities of the four accidental events are defined as $P(LDCV)$, $P(LDMV)$, $P(EES)$ and $P(EEC)$, respectively. In the DES, whether these four events occur is modeled by using a random number generator. If the generated value is smaller than the set value of probability event, an accidental event occurs, as expressed in Eqs. (5)–(8), respectively,

$$\text{Random}() \le P(LDCV) \tag{5}$$

$$\text{Random}() \le P(LDMV) \tag{6}$$

$$\text{Random}() \le P(EES) \tag{7}$$

$$\text{Random}() \le P(EEC) \tag{8}$$

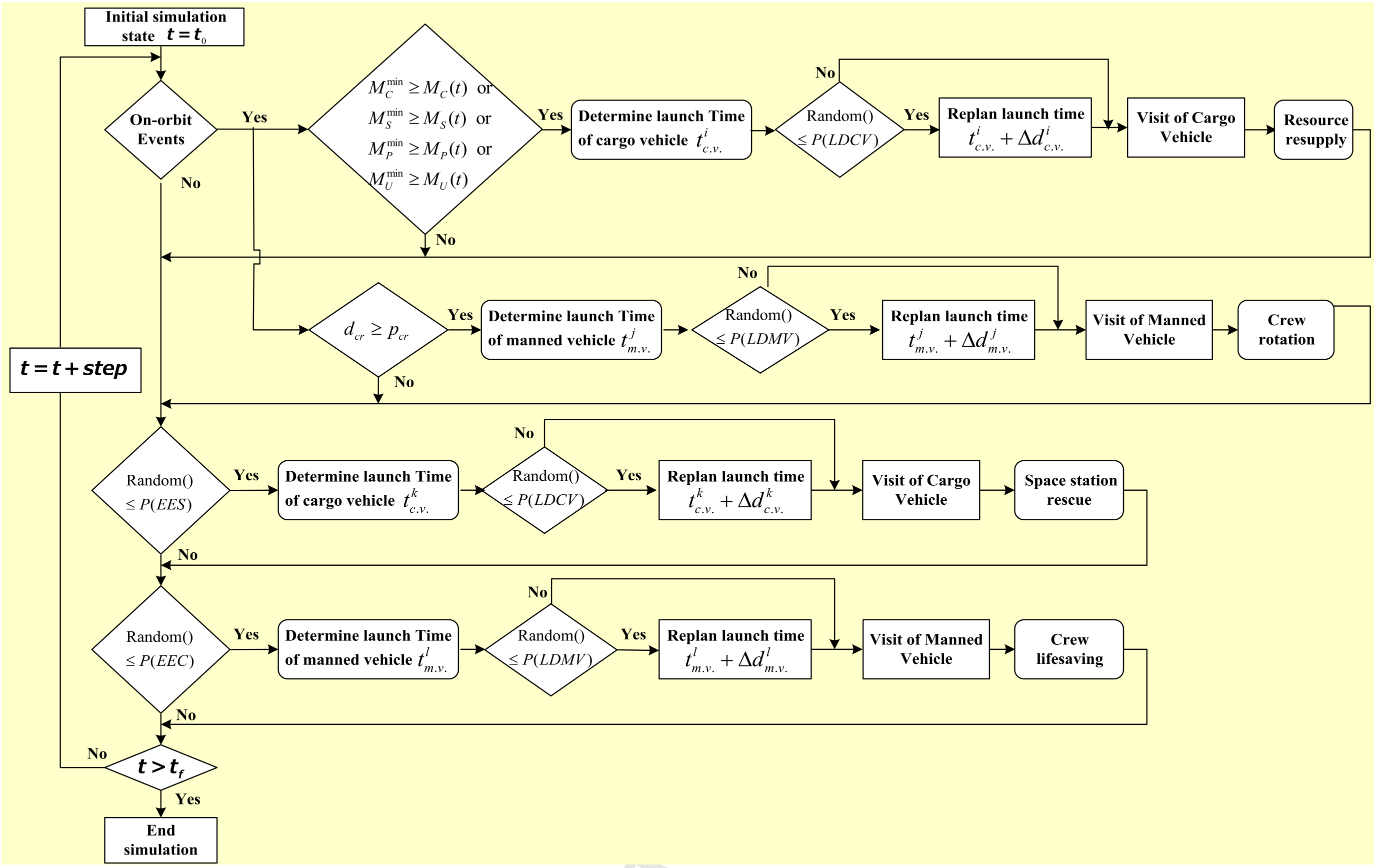

Fig. 2. Integrated simulation procedure of DES model.

where Random() represents a randomized function that generates a random variable uniformly distributed within the range of [0, 1].

Prolonged duration for extra preparation is needed once a Launch Delay of Cargo Vehicle or Launch Delay of Manned Vehicle occurs. The prolonged duration is a stochastic value, and in the DES, it is modeled by an exponential distribution, as expressed in Eqs. (9) and (10), respectively,

$$\Delta d_{c.v.} = \text{RandomExponential}() * \lambda_{c.v.} \tag{9}$$

$$\Delta d_{m.v.} = \text{RandomExponential}() * \lambda_{m.v.} \tag{10}$$

where $\lambda_{c.v.}$ defines the mean values of the prolonged duration if Launch Delay of Cargo Vehicle occurs, $\lambda_{m.v.}$ defines the mean values of the prolonged duration if Launch Delay of Manned Vehicle occurs, and RandomExponential() represents a function that generates a random variable following an exponential distribution.

3.4. Integrated simulation procedure

The DES model is able to track and record all the events that are scheduled to occur. At each simulation step, it is judged that whether any event of the ten main types is to occur. As time passes by, when an event reaches at the top of the schedule (e.g., orbital maneuvers, visits of the cargo vehicles, visits of the manned vehicles, etc.), its effects on the system (e.g., resources being consumed, needed resources becoming available, crew rotation being completed, etc.) are recorded, sometimes new events are added to the schedule, and the simulation moves on to the next event till the end time [7]. The integrated simulation procedure of the DES model is schematically illustrated in Fig. 2, and elaborated as follows.

- Whether any onboard resource approaches its minimum level

When the On-orbit Events lead to any resource decreasing to its minimum level, the Visit of Cargo Vehicle is triggered for resource resupply. The launch time of the cargo vehicle $t_{c.v.}^{i}$ is determined according to the requirement of the frequency of launches and launch window. Then, when the Launch Delay of Cargo Vehicle occurs, the launch time is modified to be $t_{c.v.}^{i} + \Delta d_{c.v.}^{i}$, where $\Delta d_{c.v.}^{i}$ is the delay duration.

- Whether astronauts' onboard time approaches rotation period

When the performance of a Crew Activity makes the astronauts' onboard time approach the limit, the Visit of Manned Vehicle needs to be arranged for a crew rotation. The launch time of the manned vehicle $t_{m.v.}^{j}$ is determined according to the rotation period and launch window. Then, when the Launch Delay of Manned Vehicle occurs, the launch time is modified to be $t_{m.v.}^{j} + \Delta d_{m.v.}^{j}$, where $\Delta d_{m.v.}^{j}$ is the delay duration.

- Whether Emergency Endangering Station occurs

When the Emergency Endangering Station takes place, a Visit of Cargo Vehicle is required for the space station rescue. Similarly, the launch time of cargo vehicle $t_{c.v.}^{k}$ is modified to be $t_{c.v.}^{k} + \Delta d_{c.v.}^{k}$ if there is a Launch Delay of Cargo Vehicle.

- Whether Emergency Endangering Crew occurs

When the Emergency Endangering Crew happens, a Visit of Manned Vehicle is triggered for crew rescue. In the same way,

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the launch time of manned vehicle $t^l_{m.v.}$ is modified to be $t^l_{m.v.} + \Delta d^l_{m.v.}$ if there is a Launch Delay of Manned Vehicle.

In an integrated simulation procedure, whether any onboard resource approaches its minimum level can be judged by whether the constraint, that the reserved resource need to be superior to its set minimum quantity, is violated, as expressed in Eq. (11),

$$\begin{cases} M_C^{\min} \le M_C(t) \\ M_S^{\min} \le M_S(t) \\ M_P^{\min} \le M_P(t) \\ M_U^{\min} \le M_U(t) \end{cases} \tag{11}$$

where $M_C^{\min}$, $M_S^{\min}$, $M_P^{\min}$, and $M_U^{\min}$ are the set minimum quantities of crew provisions, maintenance spares, propellant, and utilization materials and instruments, respectively; $M_C(t)$, $M_S(t)$, $M_P(t)$, and $M_U(t)$ refer to these four resource categories as functions of time, respectively.

Similarly, whether the onboard duration of the astronauts reaches the rotation period can be judged by whether the rotation constraint is violated, as shown in Eq. (12),

$$d_{cr} \le p_{cr} \tag{12}$$

where d_{cr} is the duration that an astronaut is aboard the space station, p_{cr} is the rotation period.

3.5. Measurable metrics

Based on the Monte Carlo simulations, five measurable metrics are defined to statistically quantify the influence of uncertainty of launch delays and onboard emergencies on nominal scenarios as follows.

- Frequency of Launch Delay of Cargo Vehicle (FLDCV)

FLDCV indicates the frequency of at least one launch delay of a cargo vehicle within a specific space station operational scenario, and it is defined as the ratio of the sum of each cargo vehicle's number of delays in all the simulation processes to the number of Monte Carlo simulations, as shown in Eq. (13),

$$\text{FLDCV} = \frac{\sum_{i=1}^{n_{cv}} N^i_{LDCV}}{N_{Monte\ Carlo}} \tag{13}$$

where $N_{Monte\ Carlo}$ is the number of the Monte Carlo simulations, n_{cv} indicates the number of cargo vehicles within a scenario, and N^i_{LDCV} means the number of delays of the ith cargo vehicle in all the simulation processes.

- Frequency of Launch Delay of Manned Vehicle (FLDMV)

FLDMV indicates the frequency of at least one launch delay of a manned vehicle within a specific space station operational scenario, and it is defined as the ratio of the sum of each manned vehicle's number of delays in all the simulation processes to the number of the Monte Carlo simulations, as expressed in Eq. (14),

$$\text{FLDMV} = \frac{\sum_{i=1}^{n_{mv}} N^i_{LDMV}}{N_{Monte\ Carlo}} \tag{14}$$

where n_{mv} indicates the number of manned vehicles within a scenario, and N^i_{LDMV} means the number of delays of the ith manned vehicle in all the simulation processes.

- Frequency of Emergency Endangering Station (FEES)

During a space station operational scenario, onboard emergency events hazarding the safety of space station might occur daily. FEES indicates the frequency of at least one Emergency Endangering Station happening within a specific space station operational scenario, and it is defined as the ratio of the sum of the number of operational scenarios within which a specific number of emergencies happen in all the simulation processes to the number of Monte Carlo simulations, as presented in Eq. (15),

$$\text{FEES} = \frac{\sum_{j=1}^{n_{EES}(\max)} N^j_{EES}}{N_{Monte\ Carlo}} \tag{15}$$

where $n_{EES}(\max)$ represents the maximum number of the emergencies happening within one scenario in all the simulation processes, n^j_{EES} means the number of scenarios within which j emergencies take place in all the simulation processes.

- Frequency of Emergency Endangering Crew (FEEC)

Similarly, during a space station operational scenario, onboard emergency events hazarding the safety of astronauts might occur daily. FEEC indicates the frequency of at least one Emergency Endangering Crew happening within a specific space station operational scenario, and it is defined as the ratio of the sum of the number of operational scenarios within which a specific number of emergencies happen in all the simulation processes to the number of Monte Carlo simulations, as shown in Eq. (16),

$$\text{FEEC} = \frac{\sum_{j=1}^{n_{EEC}(\max)} N^j_{EEC}}{N_{Monte\ Carlo}} \tag{16}$$

where $n_{EEC}(\max)$ represents the maximum number of the emergencies happening within one scenario in all the simulation processes, N^j_{EEC} means the number of scenarios within which j emergencies take place in all the simulation processes.

- Frequency of Scenario Not Duly Completed (FSNDC)

Due to the contingency event of Launch Delay of Cargo Vehicle or Launch Delay of Manned Vehicle, the actual continuous duration needed for the tested space station operational scenario might be prolonged than planned. FSNDC indicates the frequency that the designed space station operational scenario is postponed, and it is defined as the ratio of the number of tested scenarios that are not duly completed in all the simulation processes to the number of Monte Carlo simulations, as calculated in Eq. (17),

$$\text{FSNDC} = \frac{N(t_{defined} < t_{actual})}{N_{Monte\ Carlo}} \tag{17}$$

where $N(t_{defined} < t_{actual})$ represents the number of scenarios of which the actual duration (t_{actual}) is longer than the defined duration ($t_{defined}$) in all the simulation processes.

4. Results

4.1. Case summary

China's future space station is anticipated to enter a sustainment phase in 2022 calendar year. The crew rotation period is three months. The manifest strategy of cargo vehicles is to firstly resupply the resource consumption prior to the current visit and then the preposition portion is averaged to transport the four kinds of resources. The cargo vehicle has an upload payload capability of $C_{c.v.} = 6.0$ tons. The manned vehicle can transport a maximum of three astronauts to the station at a time, i.e. $C_{m.v.} = 3$ men. The mean values of the exponential distributions for the delay durations after Launch Delay of Cargo Vehicle and Launch Delay of

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Table 1
Initial and minimum inventory mass of onboard resources (kg).

Onboard resources	Crew provisions	Maintenance spares	Propellant	Utilization materials and instruments
Initial inventory	3000	2500	1300	600
Minimum inventory	1620	1287	675	270

Table 2
Properties of each launch subwindow from 2022 to 2025 calendar year.

Cargo vehicle	2022 ~ 2023	No.	1st	2nd	3rd	4th	5th	6th	7th	8th
		Beginning date	14th	62nd	88th	144th	196th	246th	270th	326th
		Ending date	48th	77th	125th	176th	230th	260th	307th	358th
	2023 ~ 2024	No.	9th	10th	11st	12nd	13rd	14th	15th	16th
		Beginning date	378th	427th	452nd	508th	560th	611st	633nd	690th
		Ending date	411st	441st	489th	540th	594th	624th	672nd	722nd
	2024 ~ 2025	No.	17th	18th	19th	20th	21st	22nd	23rd	24th
		Beginning date	742nd	791st	816th	872nd	924th	974th	997th	1054th
		Ending date	775th	806th	853rd	904th	958th	988th	1036th	1086th
Manned vehicle	2022 ~ 2023	No.	1st	2nd	3rd	4th	5th	6th	7th	8th
		Beginning date	14th	63rd	89th	144th	195th	245th	270th	326th
		Ending date	48th	77th	125th	176th	230th	260th	308th	358th
	2023 ~ 2024	No.	9th	10th	11st	12nd	13rd	14th	15th	16th
		Beginning date	378th	427th	452nd	507th	559th	609th	634th	690th
		Ending date	412nd	441st	489th	540th	594th	624th	672nd	722nd
	2024 ~ 2025	No.	17th	18th	19th	20th	21st	22nd	23rd	24th
		Beginning date	742nd	791st	816^{h}	871st	923rd	973rd	997th	1054th
		Ending date	775th	806th	854th	904th	958th	988th	1036th	1086th

Manned Vehicle occur are set as $\lambda_{c.v.} = 30$ day and $\lambda_{m.v.} = 20$ day, respectively.

The mass of crew provisions required to support an astronaut for one day is assumed to be 6.0 kg, the estimated mass of spares required per day is 14.3 kg, and the nominal consumption rate of utilization materials and instruments per day on the space station is 3 kg [19]. Moreover, based on the results of orbital numerical simulation [4], the nominal consumption rate of propellant is assumed to be 7.5 kg/day. The initial and minimum inventory quantities of resources onboard the space station are set and listed in Table 1.

Launch windows of cargo vehicles and manned vehicles are calculated separately using the filtering approach described in [3], which gradually eliminates time intervals not satisfying the constraint of angle between the Sun and orbital plane—i.e., beta angle β. Herein, beta angle constraint is set to be $|\beta| \le 40°$ and search time interval is from UTCG January 1, 2022, 0:00:00.0 to January 1, 2025, 0:00:00.0. The results are presented in Table 2, including each subwindow's beginning and ending dates. It shows that there are 24 available subwindows to constrain the visits of both the cargo vehicles and manned vehicles. Based on the launch window constraints, the launch dates of the cargo and manned vehicles are chosen to be the nearest day to the deadline when any onboard resource decreases toward its minimum value and the duration of the astronauts stay onboard approaches the rotation period, respectively.

Though simplification has been made here, such as the nominal consumption rate of onboard resources, these assumptions do not significantly affect the usefulness of the operational scenario simulation at the strategic level of analysis.

4.2. Nominal simulation results and influences by launch delays

The nominal scenario tested is for the entire year 2022 during which the space station is staffed with three astronauts, and three maintenance maneuvers (Maneuver-I, Maneuver-II, Maneuver-III) are required and executed on the 113rd, 243rd and 345th day, respectively, through the orbital numerical simulation [4]. The event probabilities of Launch Delay of Cargo Vehicle and Launch Delay of Manned Vehicle are set to $P(LDCV) = 0.03$ and $P(LDMV) = 0.05$.

The nominal results are obtained based on the proposed DES, wherein, three cargo vehicles (CV-I, CV-II and CV-III) are needed for resource resupply and the launch dates are on the 77th, 200th and 335th day, respectively; four manned vehicles (MV-I, MV-II, MV-III and MV-IV) are necessary for crew rotation and they are launched separately on the 91st, 176th, 260th and 350th day, respectively. In terms of the launch dates of vehicles and orbital maneuver dates, it is concluded that there are four available durations lasting for more than 30 days, during which microgravity experiments can be arranged, as depicted in Fig. 3. Seen from Fig. 3, it is clear that the four available durations are during the durations from the 1st to 77th day, 113rd to 176th day, 200th to 243rd day, and 260th to 335th day, respectively.

The influences on the tested nominal scenario by launch delays are determined using the Monte Carlo method, for which 10000 simulation trials are executed. The Frequency of Launch Delay of Cargo Vehicle and Frequency of Launch Delay of Manned Vehicle are calculated, with the results FLDCV = 0.098 and FLDMV = 0.1973. Moreover, it is found that launch delay of cargo vehicle has two major types. One is the serious delay leading to a too long delay that at least one kind of onboard resource is exhausted prior to the resupply. The other is the general delay that the minimum inventory mass of onboard resources is sufficient. However, all the launch delays of manned vehicles are serious and result in the duration of crew onboard exceeding the rotation period. For the 10000 trials, the percentage of the Serious delay of cargo vehicle, General delay of cargo vehicle and Serious delay of manned vehicle are shown in Table 3. It shows that the sum of the percents of Serious delay and General delay of cargo vehicle is exactly equal to the obtained FLDCV = 0.098.

Furthermore, a serious delay situation and a general delay situation are taken as instances to reveal the impacts caused by Launch Delay of Cargo Vehicle. The launch dates and payload manifests of cargo vehicles of these two representative examples as well as the nominal situation are listed in Table 4. From Table 4, it is concluded that all the launch dates of cargo vehicles satisfy the launch window constraints listed in Table 2; each cargo vehicle's total

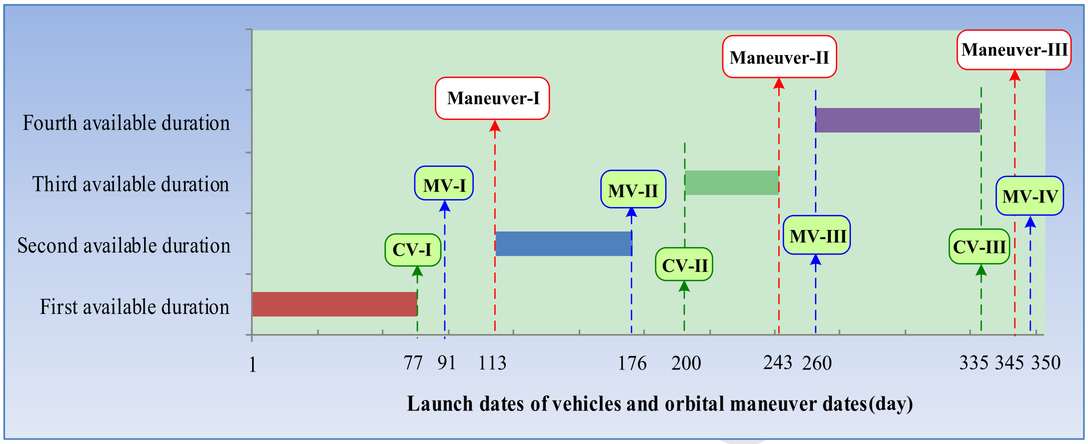

Fig. 3. Available durations lasting for more than 30 days.

Table 3
Percentage of launch delays.

Serious delay of cargo vehicle	General delay of cargo vehicle	Serious delay of manned vehicle
0.0918	0.0062	0.1973

Table 4
Launch dates and payload manifests of cargo vehicles.

Situation	Cargo vehicle	Launch date (day)	Crew provisions (kg)	Propellant (kg)	Maintenance spares (kg)	Utilization materials and instruments (kg)
Nominal	CV-I	77th	2206.47	820.47	1921.58	1051.48
	CV-II	200th	2441.03	977.03	1985.93	596.01
	CV-III	335th	2551.13	871.13	2051.63	526.11
Serious delay	CV-I	196th	2760.28	586.79	2192.89	460.04
	CV-II	230th	1811.95	1199.95	1686.15	1301.95
	CV-III	331st	2239.18	1171.18	1865.48	724.16
General delay	CV-I	77th	2206.47	820.47	1921.58	1051.48
	CV-II	224th	2661.22	765.22	2117.32	456.24
	CV-III	345th	2235.18	1557.18	1787.48	420.16

Table 5
Masses of resources at each resupply increment (kg).

Situation	Resource	First increment		Second increment		Third increment		Fourth increment	
		Initial	Terminal	Initial	Terminal	Initial	Terminal	Initial	Terminal
Nominal	C	3000	1614	3820.5	1606.5	4047.5	1617.5	4168.6	3628.6
	P	1300	1300	2120.5	1370.5	2347.5	1597.5	2468.6	1718.6
	M	2500	1398.9	3320.5	1561.6	3547.5	1617	3668.6	3239.6
	U	600	369	1420.5	1051.5	1647.5	1242.5	1768.6	1678.6
Serious delay	C	3000	**−528**	2232.3	1620.3	3432.2	1614.2	3853.4	3241.4
	P	1300	550	1136.8	1136.8	2336.7	1586.7	2757.9	2007.9
	M	2500	**−302.8**	1890.1	1403.9	3090	1645.7	3511.2	3025
	U	600	12	472	370	1672	1369	2093.2	1991.2
General delay	C	3000	1614	3820.5	1174.5	3835.7	1657.7	3892.9	3532.9
	P	1300	1300	2120.5	1370.5	2135.7	635.7	2192.9	2192.9
	M	2500	1398.9	3320.5	1218.4	3335.7	1605.4	3392.9	3106.9
	U	600	369	1420.5	979.5	1435.7	1072.7	1492.9	1432.9

mass of payload manifests satisfies the upload payload capability of $C_{c.v.} = 6.0$ t; in the serious delay situation, the launch date of CV-I is postponed from the 77th day to 196th; and in the general delay situation, the launch date of CV-II is postponed from the 200th day to 224th.

Additionally, the masses of resources at each resupply increment's initial and terminal time are given in Table 5, wherein C, P, M, U represent the crew provisions, propellant, maintenance spares, utilization materials and instruments, respectively. It shows that, during an increment, for each kind of resource, the initial mass subtracts the terminal mass is the total consumed mass, and the terminal mass adds the upload resupply of cargo vehicle is equal to the initial mass of next increment. In the serious delay situation, the masses of crew provisions and maintenance spares at the terminal of the first increment are minus, meaning insufficient due to the delay. In the general delay situation, all the onboard resources are adequate in despite of the delay, because of the minimum inventory quantities of onboard resources as set in Table 1.

Similarly, one serious delay situation of manned vehicles is chosen to further analyze the influence. The deadline for crew rotation

Table 6
Deadline and launch dates of cargo vehicles (day).

Situation	MV-I		MV-II		MV-II		MV-IV	
	Deadline	Launch date	Deadline	Launch date	Deadline	Launch date	Deadline	Launch date
Nominal	91st	91st	181st	176th	266th	260th	350th	350th
Serious delay	91st	91st	181st	176th	266th	**272nd**	362nd	358th

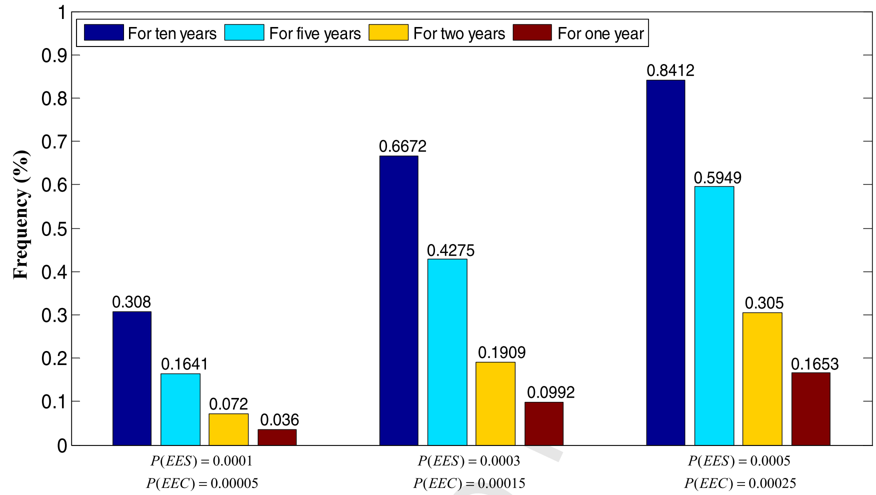

Fig. 4. Frequencies of Emergency Endangering Station (FEES).

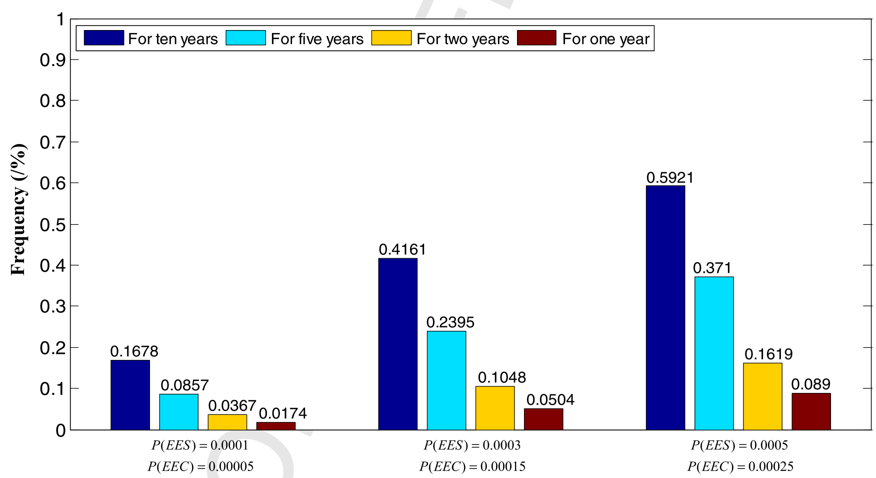

Fig. 5. Frequencies of Emergency Endangering Crew (FEEC).

and the launch dates of both the nominal and serious delay situations are presented in Table 6. It shows that the launch delay occurs at the third rotation mission and MV-III is postponed to launch on the 272nd day; the replanned launch time of a delayed manned vehicle exceeds the deadline for rotation, which should be paid attention to by the space station mission designers.

4.3. *Frequencies of onboard emergencies*

In this section, in order to analyze the onboard emergencies, three sets of event probabilities of both Emergency Endangering Station and Emergency Endangering Crew are designed, combining $P(EES) = 0.0001$ and $P(EEC) = 0.00005$, $P(EES) = 0.0003$ and $P(EEC) = 0.00015$, $P(EES) = 0.0005$ and $P(EEC) = 0.00025$; and four operational scenarios are tested, whose durations last for ten years, five years, two years and one year, respectively. Monte Carlo method is employed to obtain the frequencies of emergencies, for which 10000 simulation trials are executed.

The statistical frequencies of emergencies by Emergency Endangering Station and Emergency Endangering Crew are presented in Fig. 4 and Fig. 5. They show that, for the Emergency Endangering Station or Emergency Endangering Crew, each day's probabilities will most likely lead to the occurrence of the accidental events during a long-duration space station operational scenario, which suggests to the mission designers that contingency measures should be planned for; during a specific scenario, the frequency of Emergency Endangering Station or Emergency Endangering Crew increases with both the higher event probabilities and the longer operational scenarios.

Furthermore, the percentage of the times of emergencies occurred are provided in detail in Table 7, Table 8 and Table 9. They show that the frequency of emergencies increases with both the higher event probabilities and the longer operational scenarios; for a specific frequency of Emergency Endangering Station or Emergency Endangering Crew, the percent of the times of emergencies occurred decreases with the higher times.

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Table 7
Percents of times of emergencies for $P(EES) = 0.0001$ and $P(EEC) = 0.00005$.

Emergency	Duration	Total frequency	Times				
			One	Two	Three	Four	Five
Emergency Endangering Station	ten years	0.308	0.2551	0.0473	0.0049	0.0006	0.0001
	five years	0.1641	0.1502	0.0132	0.0007	0	0
	two years	0.072	0.0693	0.0027	0	0	0
	one year	0.036	0.0353	0.0007	0	0	0
Emergency Endangering Crew	ten years	0.1678	0.1508	0.0161	0.0009	0	0
	five years	0.0857	0.0819	0.0037	0.0001	0	0
	two years	0.0367	0.0361	0.0006	0	0	0
	one year	0.0174	0.0172	0.0002	0	0	0

Table 8
Percents of times of emergencies for $P(EES) = 0.0003$ and $P(EEC) = 0.00015$.

Emergency	Duration	Total frequency	Times					
			One	Two	Three	Four	Five	Six
Emergency Endangering Station	ten years	0.6672	0.366	0.2047	0.0723	0.0192	0.0044	0.0006
	five years	0.4275	0.3207	0.0886	0.0154	0.0023	0.0005	0
	two years	0.1909	0.17	0.0198	0.001	0.0001	0	0
	one year	0.0992	0.0938	0.0054	0	0	0	0
Emergency Endangering Crew	ten years	0.4161	0.3112	0.0853	0.0167	0.0029	0	0
	five years	0.2395	0.2087	0.0279	0.0026	0.0003	0	0
	two years	0.1048	0.0989	0.0057	0.0002	0	0	0
	one year	0.0504	0.0493	0.0011	0	0	0	0

Table 9
Percents of times of emergencies for $P(EES) = 0.0005$ and $P(EEC) = 0.00025$.

Emergency	Duration	Total frequency	Times							
			One	Two	Three	Four	Five	Six	Seven	Eight
Emergency Endangering Station	ten years	0.8412	0.2904	0.2716	0.1681	0.075	0.0256	0.0084	0.0015	0.0006
	five years	0.5949	0.3607	0.1659	0.0531	0.0127	0.0023	0.0002	0	0
	two years	0.305	0.2546	0.0439	0.006	0.0005	0	0	0	0
	one year	0.1653	0.1511	0.0133	0.0008	0.0001	0	0	0	0
Emergency Endangering Crew	ten years	0.5921	0.3566	0.1691	0.0531	0.0098	0.0031	0.0003	0.0001	0
	five years	0.371	0.2932	0.067	0.0095	0.0012	0.0001	0	0	0
	two years	0.1619	0.1469	0.0139	0.0011	0	0	0	0	0
	one year	0.089	0.0857	0.0033	0	0	0	0	0	0

Table 10
Each vehicle's launch date for demonstrating delay (day).

Situation	MV-I	CV-I	MV-II	CV-II	MV-III	CV-III	MV-IV
Nominal	152nd	213rd	335th	397th	517th	578th	700th
Delay by MV-I	***176th***	230$^{\text{th}}$	352nd	427th	534th	611st	717th
Delay by CV-I	152nd	***228th***	350th	470th	575th	636th	758th
Delay by MV-II	152nd	213rd	***351st***	427th	537th	611st	720th
Delay by CV-II	152nd	213rd	335th	***403rd***	523rd	584th	742nd
Delay by MV-II	152nd	213rd	335th	397th	***525th***	586th	708th
Delay by CV-II	152nd	213rd	335th	397th	517th	***588th***	710th
Delay by MV-IV	152nd	213rd	335th	397th	517th	578th	***742nd***

4.4. Assessment of completion of long-duration scenario

In this section, the proposed DES approach is employed to assess the completion of a two-year space station operational scenario from January 1, 2022 to December 31, 2023, which incorporates four rotation missions of the manned vehicles (MV-I, MV-II, MV-III and MV-IV) and three resupply missions of the cargo vehicles (CV-I, CV-II and CV-III). MV-I is scheduled to launch on June 1, 2022 or the 152nd day, and CV-I is launched two months later, i.e. on August 1, 2022 or the 213rd day. The tested scenario is set to be completed on December 1, 2023 or the 700th day, when MV-IV is launched. The intervals between the two successive manned vehicles and the two successive cargo vehicles are set to be six months, and each vehicle's nominal scheduled launch date is set and listed in Table 10. Two sets of event probabilities of Launch Delay of Cargo Vehicle and Launch Delay of Manned Vehicle are considered, including $P(LDCV) = 0.03$ and $P(LDMV) = 0.05$, $P(LDCV) = 0.05$ and $P(LDMV) = 0.1$, and 10000 trials are executed using the Monte Carlo method.

Among the simulation results, seven scenarios not duly completed caused by the first delay of MV-I, CV-I, MV-II, CV-II, MV-III, CV-III and MV-IV, respectively, are chosen and listed in Table 10, in order to properly demonstrate the launch delay of each visit vehicle. The prolonged durations after launch delay happened are calculated based on the Eqs. (9) and (10). Table 10 indicates that once a Launch Delay of Cargo Vehicle or Launch Delay of Manned Vehicle occurs, one specific operational scenario will most likely be not duly completed.

Table 11
Frequencies of the tested scenario not being completed.

Probabilities	Frequencies		
	FSNDC	Launch Delay of Cargo Vehicle	Launch Delay of Manned Vehicle
$P(LDCV) = 0.03$ $P(LDMV) = 0.05$	**0.2303**	0.0928	0.1524
$P(LDCV) = 0.05$ $P(LDMV) = 0.1$	**0.3886**	0.1407	0.2864

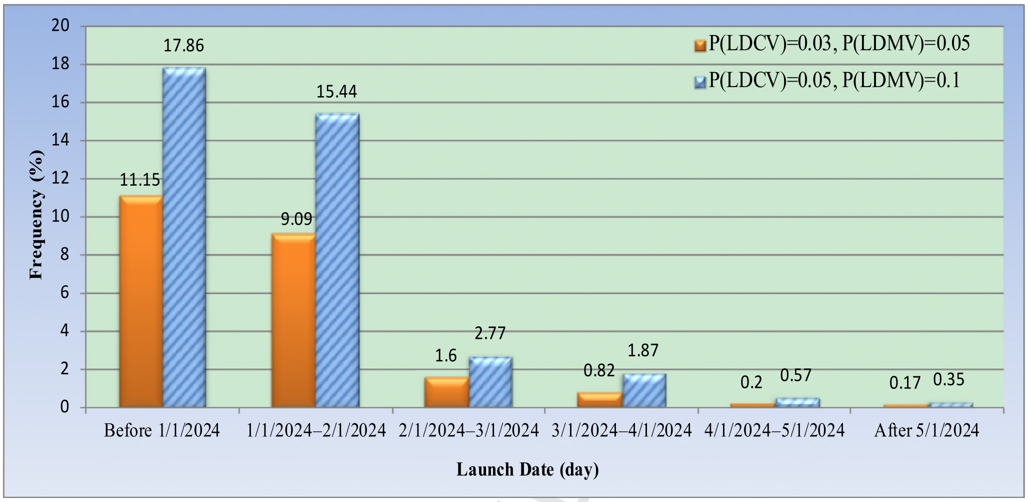

Fig. 6. Frequencies of the launch date of MV-IV within completion delay situations.

The Frequency of Scenario Not Duly Completed (FSNDC), as well as the frequencies caused by Launch Delay of Cargo Vehicle and Launch Delay of Manned Vehicle, are shown in Table 11. Further, within the completion delay situations, the percentage of the launch date of MV-IV, namely the duration for completing the scenario, are drawn depicted in Fig. 6. This application for analyzing the completion delay is in some extent similar to the studies in [14–16] using a DES to model the assembly of the ISS, yet it also provides visual estimate of the last launch date for the mission designers, which is helpful to arrange the long-duration operation of China's future space station.

5. Conclusions

A DES method is developed to support China's space station research in the top-level design of the on-orbit and the logistics missions. The DES schematizes the simulation of space station operations as a discrete event system, which comprises ten main types of events: Repair and Replacement, Experiment and Utilization, Orbital Maneuver, Crew Activity, Visit of Cargo Vehicle, Visit of Manned Vehicle, Launch Delay of Cargo Vehicle, Launch Delay of Manned Vehicle, Emergency Endangering Station and Emergency Endangering Crew. The integrated simulation procedure is developed, wherein launch delays and onboard emergencies are contingency events with probabilities, and the possible duration used to prepare the next launch if delay occurs follows the exponential distributions. Based on the Monte Carlo simulations, the metrics of Frequency of Launch Delay of Cargo Vehicle (FLDCV), Frequency of Launch Delay of Manned Vehicle (FLDMV), Frequency of Emergency Endangering Station (FEES), Frequency of Emergency Endangering Crew (FEEC), and Frequency of Scenario Not Duly Completed (FSNDC) are defined to quantify the stochastic impacts of the launch delays and the onboard emergences. In terms of the demonstration for the notional operations of China's future space station, three major conclusions can be drawn. 1) Whether the launch delay of cargo vehicle could cause the exhaustion of onboard resources depends on both the prolonged duration and resources' minimum inventory masses. 2) Launch delay of manned vehicle generally leads to the duration of crew onboard exceeding the rotation period. 3) Contingency measures should be prepared in case of the onboard emergencies during a long-duration scenario.

Conflict of interest statement

None declared.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.ast.2017.05.037.

References

[1] Y.Z. Wang, Launching manned space station project and promoting the development of China's manned space engineering, Manned Spaceflight 17 (2011) 1–4 (in Chinese).
[2] K.P. Lin, Y.Z. Luo, G.J. Tang, Space station orbit design using dynamic programming, Acta Astronaut. 89 (2013) 195–204.
[3] K.P. Lin, Y.Z. Luo, J. Zhang, et al., Planning for space station long-duration orbital mission under multi-constraints, Sci. China, Technol. Sci. 56 (5) (2013) 1075–1085.
[4] K.P. Lin, Y.Z. Luo, G.J. Tang, Optimization of logistics strategies for long-duration space station operation, J. Spacecr. Rockets 51 (5) (2014) 1709–1720.
[5] K.P. Lin, Y.Z. Luo, J. Zhang, et al., Space station overall mission planning using decomposition approach, Aerosp. Sci. Technol. 33 (2014) 26–39.
[6] P. Legato, R.M. Mazza, Berth planning and resources optimisation at a container terminal via discrete event simulation, Eur. J. Oper. Res. 133 (3) (2001) 537–547.

[7] M.J. Kelly, A.C. Charania, J.R. Olds, D. DePasquale, Discrete event simulation of reusable launch vehicle development, acquisition, and ground operations, in: AIAA Space 2009 Conference and Exposition, Pasadena, California, September 14–17, 2009, 2009, AIAA 2009-6484.

[8] M.R. Jardin, D. Manegold, A. Apte, Discrete-event simulation of air traffic flow, in: AIAA Guidance, Navigation, and Control Conference, Toronto, Ontario Canada, August 2–5, 2010, 2010, AIAA 2010-7853.

[9] S. Jafer, Q. Liu, G. Wainer, Object-oriented discrete event simulation modeling environment for aerospace vehicle maintenance and logistics process, Proc. Comput. Sci. 16 (2013) 187–196.

[10] S. Robinson, C. Worthington, N. Burgess, Z.J. Radnor, Facilitated modelling with discrete-event simulation: reality or myth?, Eur. J. Oper. Res. 234 (1) (2014) 231–240.

[11] O. de Weck, N. Armar, P. Grogan, et al., A flexible architecture and object-oriented model for space logistics simulation, in: AIAA Space 2009 Conference and Exposition, Pasadena, California, September 14–17, 2009.

[12] A. Siddiqi, O.L. de Weck, G.Y. Lee, et al., Matrix modeling methods for space-flight campaign logistics analysis, J. Spacecr. Rockets 46 (5) (2009) 1037–1048.

[13] P.T. Grogan, H.K. Yue, O.L. de Weck, Space logistics modeling and simulation analysis using SpaceNet: four application cases, in: AIAA Space 2011 Conference and Exposition, Long Beach, California, September, 27–29, 2011, 2011, AIAA 2011-7346.

[14] G.R. Cates, Improving Project Management with Simulation and Completion Distribution Functions, Doctoral dissertation, Department of Industrial Engineering and Management Systems, University of Central, Florida, Orlando, Florida, 2004, pp. 10–30.

[15] G.R. Cates, M. Mollaghasemi, A discrete event simulation model for assembling the international space station, in: Proceedings of the 37th Conference on Winter Simulation, 2005, pp. 1260–1264.

[16] G.R. Cates, M. Mollaghasemi, Supporting the vision for space with discrete event simulation, in: Proceedings of the 37th Conference on Winter Simulation, 2005, pp. 1306–1310.

[17] L. Trocine, N.H. Cummings, A.M. Bazzana, et al., Statistical and probabilistic extensions to ground operations' discrete event simulation modeling, in: AIAA SpaceOps 2010 Conference, Huntsville, Alabama, April, 25–30, 2010, 2010, AIAA 2010-2027.

[18] E. Messerschmid, R. Bertrand, Space Stations Systems and Utilization, Springer Verlag, Berlin, Heidelberg, Germany, 1999, pp. 205–237.

[19] S. Shull, O. de Weck, Modeling and simulation of lunar campaign logistics, in: AIAA Space 2007 Conference & Exposition, Long Beach, California, September 18–20, 2007, 2007, AIAA 2007-6244.

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