CONCURRENT ENGINEERING AND SOCIAL DISTANCING 101: LESSONS LEARNED DURING A GLOBAL PANDEMIC

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ABSTRACT

Social distancing measures introduced in the wake of COVID-19 greatly impacted the concurrent engineering process. This paper addresses methodological adaptation measures which are required to ensure the continuity of this activity. Two CubeSat feasibility studies run at the University of Strathclyde, one physical and one virtual, are compared to quantify the impact of the adaptation. Three evaluation criteria are used: the fulfilment of requirements & customer satisfaction, server data flow rate and participant perceptions. The results indicate that although adaptation was successful, it failed to lift all communication barriers introduced by virtual exchanges.

1. INTRODUCTION

On 11th March 2020, the Director-General of the World Health Organization declared the novel coronavirus disease 2019 (COVID-19) a global pandemic, prompting the need for immediate targeted action to reduce the chances of infection [1]. In this regard, the introduction of social distancing measures became a key and often mandatory preventive strategy in many countries to delay the epidemic peak so that healthcare systems were able to cope with an increased influx of patients. The suspension of face-to-face contact and non-essential travel for workers has serious implications for many sectors and workplace activities, including the concurrent engineering (CE) process of products. This approach requires engineers to work systematically and collaboratively within the same facility in order to decrease the need for multiple design reworks [2].

Therefore, until lifted, the implementation of social distancing measures leaves two possibilities for its application: either suspend all CE activities or attempt them remotely. Although it is unclear how the latter option would impact the quality of the CE process, it is evidently the more appealing approach despite the unprecedented challenges and obstacles that it may present. This is because it minimises interruption to business whilst continuing to drive innovation.

Accordingly, the aim of this paper is to quantify the implications of a virtual CE session in comparison to a physical CE session. This analogy is based on two CubeSat design studies performed at the University of Strathclyde. The successes, challenges and lessons learned from the virtual CE study will be presented including any issues/obstacles faced and how these were embraced/overcome.

2. BACKGROUND & OVERVIEW

2.1. Impact of Social Distancing Measures on University Concurrent Engineering Activities

After closely monitoring the escalation and spread of COVID-19 within the UK, the University of Strathclyde made the decision to suspend all face-to-face teaching from 16th March 2020 and closed almost all university facilities from 20th March 2020. This approach was then made compulsory by Prime Minister Boris Johnson in an address to the UK on 23rd March 2020, where it was announced that the UK would enter a mandatory lockdown to enforce social distancing [3]. This became a legal requirement within Scotland on 26th March 2020 through the Health Protection (Coronavirus) (Restrictions) (Scotland) Regulations 2020 [4]. Whilst lockdown restrictions began to gradually ease in the following months, social distancing measures remained firmly in place.

As a result, the University of Strathclyde has remained closed, with its students and staff all encouraged to work from home if possible. Currently, it looks highly unlikely that the university will reopen before September/October 2020 at the earliest, through a measured and phased approach with social distancing and other public health measures put in place. This has serious implications for CE activities at the university due to the copious amount of teamwork involved. The University of Strathclyde has its own Concurrent Design Facility (CDF) called the Concurrent & Collaborative Design Studio (CCDS). This facility was opened in October 2015 and is located within the Technology & Innovation Centre in Glasgow. It is used for all CE activities within the university and consists of 18 workstations, each of which are equipped with Linux (Ubuntu 14.04) and Windows 7 operating systems. The CCDS uses both the European Space Agency (ESA) Open Concurrent Design Tool (OCDT) and RHEA Group's Concurrent Design & Engineering Platform 4 - Community Edition (CDP4-CE) as central design tools hosted on an Ubuntu 14.04.4 virtual server. However, access to this facility has not been permitted since the closure of the university. Nonetheless, since co-location is embedded as one of the basic principles of CE, this means that in its traditional form, CE is theoretically incompatible with social distancing measures. For this reason, rather than suspend all CE activities at the university, the Director of the Aerospace Centre of Excellence opted to continue these studies in a virtual format for the first time.

2.2. Designing a Space Mission in Isolation

In the frame of the mandatory social distancing measures put in place due to COVID-19, the University of Strathclyde conducted a virtual CE study for a Phase 0 spacecraft design between 22nd May and 29th May 2020. The mission was named STRATHcube and involved 29 participants. The spacecraft is a 3U CubeSat, developed in support of an internal student-led application for ESA Education's 'Fly Your Satellite' programme. This was the first fully virtual feasibility study run by the University of Strathclyde. The primary payload is a 3D phase array antenna for space debris detection. Several heat flux and pressure sensors, as well as UV and visual spectrometers, are integrated to perform measurements during re-entry. A third experiment involves a laser on-board the International Space Station (ISS), from which the CubeSat could be launched, to attempt wireless power transmission (WPT). ESA Education provides a lengthy requirement list for the spacecraft design [5], including a minimum lifetime of 6 months. Mission analysis was a mission driver for balancing the ballistic coefficient and mission duration, leading to the discard of the propulsion system and thus greatly reducing costs.

Evidently, conducting this study entirely virtually required alterations to be made to the traditional CE approach that is usually adopted within physical studies. Therefore, in order to test the relative success of the adapted methodology applied within the STRATHcube study (see Section 3.1), a comparison needs to be made to a similar physical design study. As such, the NEACORE mission was deemed the most appropriate for this purpose due to the similarity of its mission class (considering the limited pool of studies conducted at the CCDS). Figure 1 presents the configuration of each spacecraft, which both primarily rely on commercial off-the-shelf components.

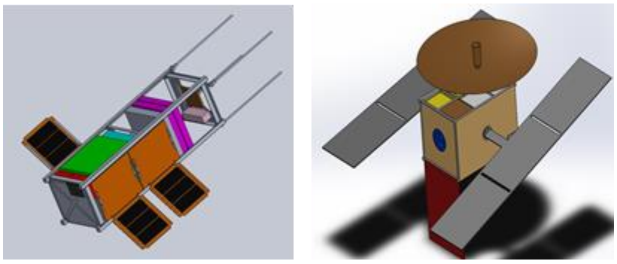

Figure 1. STRATHcube (left) and NEACORE (right)

Specifically, NEACORE is an interplanetary mission involving up to six 12U CubeSats, to be flown on a single launcher between 2022 and 2023. The mission aims to estimate the relative position, velocity and 2D shape of near-Earth objects. The feasibility study was run between 29th April and 3rd May 2019 within the CCDS and included 17 participants. The spacecraft design needed to be flexible to accommodate a camera and either a LIDAR or spectrometer. The sizing of the on-board data handling subsystem was a mission driver as all flyby data had to be stored for the full mission duration. Configuration was also a challenge since the mission required a large deep space antenna to be accommodated as well as a LIDAR reflector mirror. The mission is expected to last between 3 and 6 years, with a low thrust propulsion system.

As such, within this paper, the STRATHcube study is used to represent a virtual CE session. This will be compared against the NEACORE study which is used to represent a physical design session.

3. MATERIALS & METHODS

3.1. Adaptation of the Traditional Concurrent Engineering Methodology

Since the CCDS is still a relatively new facility which is mainly used by students, the methodology applied within each physical CE study run at the university thus far has been based upon the ESA CE philosophy, as exemplified through ESA Academy's CE challenge [6,7]. As the participants of the STRATHcube study would rely almost exclusively on video conferencing to discuss and connect remotely to the CCDS, this meant that more than ever, the centralisation of subsystem data on the server was essential to maintain sight of the design evolution. This clearly required the traditional methodology applied within previous physical CE sessions run from the university's CCDS to be adapted in order to sustain a virtual CE session. As such, several measures were taken to appropriately modify the methodology by taking into account a wide array of technical, procedural and behavioural differences. The actions taken with respect to each of these aspects are summarised in Figure 2.

Figure 2. Measures of adaptation to a virtual concurrent engineering study

3.2. Measuring the Influence of the Methodological Adaptation on a Virtual Study

To assess the impact of the methodological adaptation on the outputs of the STRATHcube study, three evaluation parameters were selected. Firstly, the quality of design was determined based on the fulfilment of mission and payload requirements, as well as customer satisfaction levels. Secondly, the dynamism of the engineering session was measured via the flow of data passing through the server. Finally, two research surveys were distributed amongst the participants of the virtual CE study to gather their impressions of the process. For each of the parameters, the STRATHcube study is compared against the NEACORE study to benchmark the impact of the methodological adaptation.

In terms of the first parameter, assessing the quality of a feasibility study is a complex task. If this was solely based on the judgement of the team that designed the spacecraft, it is highly likely that bias or exaggeration would occur [8]. Therefore, to ensure objectivity, the level of mission definition and design quality was measured through the achievement of mission and payloads requirements, as well as customer satisfaction levels using a feedback survey. The mission and payload requirements of each project were agreed upon during the pre-study phase when setting the goals and boundaries. A requirement will be considered as 'fulfilled' when it has been integrated into the system design and transcribed into detailed specifications.

The flow of data through the server can be measured by analysing the total number of commits made within each engineering model and then running a chi-squared test of independence. A commit is considered to be a parameter value that has been sent for publication by a discipline (which has been approved and released into the engineering model by the system engineers). A chi-square test of independence is used to establish whether the values of one categorical variable depend upon the values of another categorical variable [9]. Therefore, the test was applied in order to determine whether there was a statistically significant relationship between the number of commits made per iteration and design session type.

Finally, two research surveys were distributed to study participants to quantify their impressions on the virtual CE session. The first was sent to nine individuals who participated in both the NEACORE and STRATHcube studies (Group A). This survey sought to compare the levels of participant interaction, study flexibility and understanding of the process between design session type. The second survey was sent to twenty-five individuals in total which included the nine from Group A plus a further sixteen who did not participate in the NEACORE study but did participate in the STRATHcube study (Group B). This survey related to participant impressions of the virtual CE session (before, during and after). The information from both research surveys have been used collectively to frame successes, challenges and lessons learned from this virtual CE study. A 100% response rate was achieved for both surveys.

4. RESULTS & ANALYSIS

4.1. Fulfilment of Requirements & Levels of Customer Satisfaction

Overall, each mission design achieved similar levels of requirement completion (as shown in Table 1). However, the variations observed in the fulfilment of mission and payload requirements may be due to contrasting mission objectives and complexity levels rather than design session type. Indeed, NEACORE is a deep space mission requiring a propulsion system and several mechanisms to accommodate a large antenna and payloads. It was thus more complex to complete NEACORE's mission requirements. On the other hand, STRATHcube is more ambitious payload-wise, with three experiments on-board while NEACORE limited itself to two payloads per spacecraft. These factors may offer an explanation as to why the STRATHcube study fulfilled more of its mission requirements and less of its payload requirements than the NEACORE study.

Table 1. Fulfilment of study requirements

Requirement Type	**NEACORE**		**STRATHcube**	
	Total (n)	**Fulfilled (%)**	**Total (n)**	**Fulfilled (%)**
Mission	10	80%	11	91%
Payload(s)	7	86%	14	79%
Total	17	82%	25	84%

In the case of NEACORE, a mission requirement left unfulfilled was the final mass budget which was 24g over the mass limit of 24kg for the design option which included the LIDAR payload. The volume and mass of the LIDAR was under-estimated, failing to meet the payload requirement. Regarding the STRATHcube mission requirements, the main issue was that not all components had been confirmed free of export control restrictions. Additionally, the analysis showed that the semi-controlled re-entry might not be feasible, jeopardising re-entry measurements below an altitude of 130km. Finally, uncertainties concerning the ΔV, angle of spacecraft ejection from the deployer and the laser range meant that it was dubious whether the spacecraft would be capable of remaining in proximity of the ISS long enough to perform the WPT experiment. Further analysis with higher fidelity models of the satellite motion are still to be run.

Since the Director of the Aerospace of Excellence requested both studies, he is considered to be the customer. Overall, he was very satisfied with both studies mentioning the "tremendous work" and "great results" achieved. However, from his perspective, although both missions reached a "very similar level of design completeness", NEACORE appeared to be more successful since it was a more ambitious project. The customer underlined a few points to address further in order to improve the output quality of future studies. For instance, the preparatory work ahead of the next design session should be longer than a few days (at subsystem level) and weeks (at system level). Additionally, the next iteration could include more experts to assist students who have little experience or background skills in CE.

4.2. Flow of Data through the Server

The amount of data collected within the NEACORE and STRATHcube CE studies have been used to determine the impact of the methodological adaptation since it provides an indicative gauge on the level of detail within each study. As such, Figure 3 and 4 map the flow of data through the server, measured by the total number of commits throughout each study.

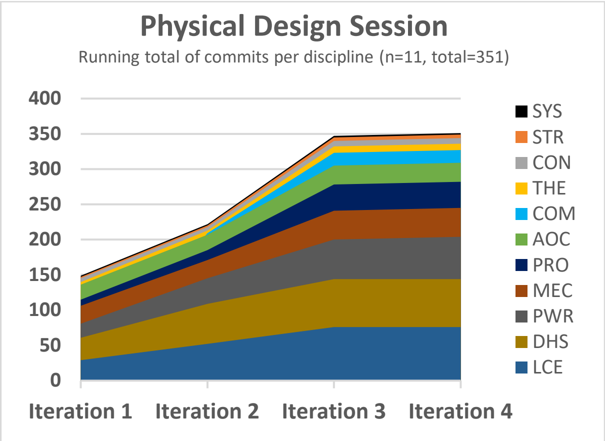

Figure 3. Total number of commits made by each discipline in the NEACORE study

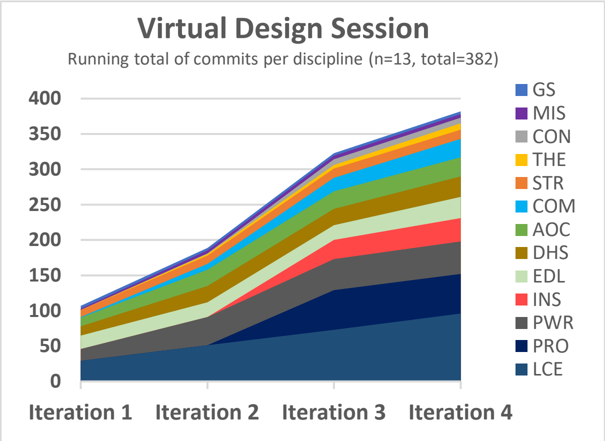

Figure 4. Total number of commits made by each discipline in the STRATHcube study

From this, it can be determined that the flow of data through the server did not drastically vary between the physical and virtual studies, with a total difference of only 31 commits over four iterations. Table 2 below summarises these findings by iteration for each study type. Using this information, it was found that the average number of commits per discipline was 31.91 for the physical design session (7.98 per iteration) compared to 29.39 for the virtual design session (7.35 per iteration).

Table 2. Number of commits according to study type

Iteration	Total commits		Average commits per discipline	
	Physical	Virtual	Physical	Virtual
1	149	107	13.55	8.23
2	73	82	6.64	6.31
3	125	134	11.36	10.31
4	4	59	0.36	4.54

In order to further analyse and compare the flow of data through the server within both physical and virtual design sessions, a chi-square test of independence was conducted to determine whether there is a significant association between the total commits made per iteration and design session type. As such, the null hypothesis (H_0) and the alternative hypothesis (H_1) were set as:

H_0: The total number of commits made per iteration is independent of design session type.

H_1: The total number of commits made per iteration is dependent upon design session type.

In terms of prerequisite data requirements, it was determined that the data for total commits contained within Table 2 met the conditions for testing these hypotheses. This is because the sample data contained at least two categorical variables with two or more categories for each variable, was based on independent observations and consisted of a sufficient sample size. Therefore, the chi-squared statistic was calculated using the following equation:

$$X^2 = \sum \frac{(O - E)^2}{E} \quad (1)$$

Where X^2 is the chi-squared statistic, O is the observed values for total commits outlined within Table 2 for both physical and virtual design sessions, and E is the expected values which were obtained by multiplying the row total by the column total for each observed value before dividing this by the grand total. It should be noted that Iteration 4 was excluded from this analysis since this was a post-CE activity within the NEACORE study.

The result obtained was then compared against the critical value for X^2 at a confidence level of 95% using the appropriate degrees of freedom. Overall, it was found that the value for X^2 (6.875067) is higher than the critical value (p=0.05) at 2 degrees of freedom, meaning that the null hypothesis can be rejected. Thus, it can be concluded that a relationship exists between the total number of commits made per iteration and the type of design session. On further analysis of these findings, it was determined that the contrasting number of commits made between physical and virtual design sessions within Iteration 1 generated 61.32% of the X^2 value. This highly influenced the outcome of the chi-square test and was ultimately the reason why the result was found to be significant.

4.3. Participant Perceptions

The first research survey allowed Group A respondents (individuals who participated in both studies) to score participant interaction, study flexibility and the level of understanding of both the STRATHcube and NEACORE studies (where 6.0 is very good and 0.0 is very poor). In the justification of their scoring for each aspect, the general consensus was that although Zoom was beneficial for STRATHcube, it still left participants feeling more disconnected than the NEACORE study due to a lack of face-to-face interaction. In addition, it was felt that the progression through design options was more advanced during the STRATHcube study whilst the level of understanding remained unchanged due to increased familiarity with the CE process coupled with confusion concerning payload requirements for STRATHcube. The results of this survey can be seen in Figure 5 below.

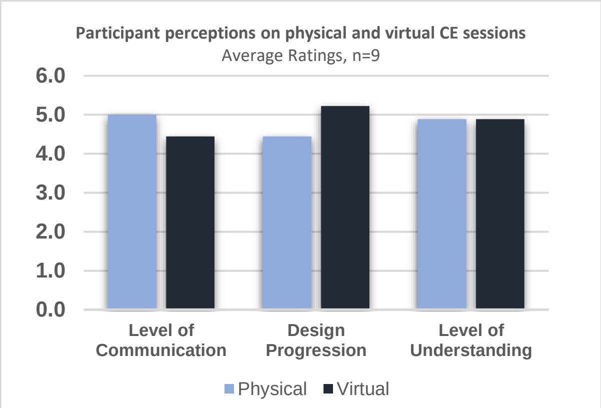

Figure 5. Participant perceptions on physical and virtual concurrent engineering sessions

The second research survey, involving all virtual study participants, found that 92% of participants thought that the mission goal and applied methodology was clear before the start of the STRATHcube study. Additionally, 76% had a clear understanding of discipline objectives whilst 96% felt that they received sufficient support installing software and setting up the required environment prior to the study. A further 92% felt satisfied with software available during the study and 96% felt that the CDP4-CE tutorial was comprehensive enough for them to grasp the tool's basic functions. Although 100% of respondents stated that they benefited from participation in the study to some degree, three issues were consistently cited by respondents. The first related to communication difficulties in the absence of a physical CDF. Respondents felt that Zoom did not fully compensate for this and the high number of channels for communication meant it was sometimes hard to keep track of new design updates. Secondly, respondents felt that the CDP4-CE had a very steep learning curve. Finally, not all participants fully understood the payload requirements before the design session began which limited their ability to conduct preparatory work.

Despite this, it is clear from Figure 6 that these issues did not greatly influence the enjoyment levels of STRATHcube study participants. Interestingly, there was no observable difference in enjoyment levels between Group A and Group B respondents. This could be due to the high levels of enthusiasm shown amongst Group B whilst the heightened familiarity and experience with the CE process may have increased the confidence of Group A (since only one individual within Group B had any previous CE experience).

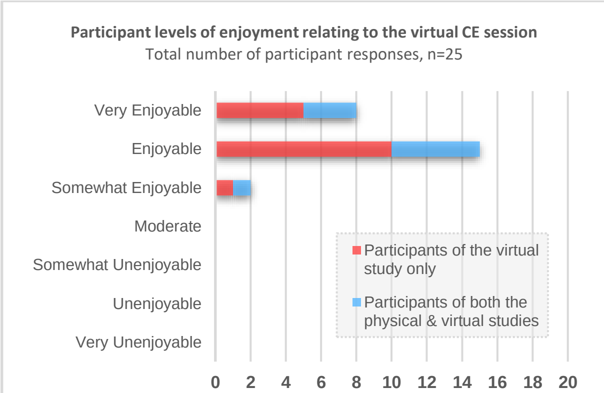

Figure 6. Participant levels of enjoyment relating to the virtual concurrent engineering session

4.4. Miscellaneous Observations

In addition to the three evaluation parameters applied within this paper, other notable aspects of the virtual CE session were observed and documented by the system engineers. These aspects have been split into technical, procedural and behavioural issues as presented in Table 3 below. It should be noted that although the table intends to highlight issues and challenges, there were still distinct positive outcomes. This will be discussed further in the following sections in order to evaluate the successes, challenges and lessons learned from the virtual CE study.

Table 3. Other notable observations of the virtual concurrent engineering study

	Technical	Procedural	Behavioural
Pre-Study	❌ Some struggles emerged dealing with different OS, poor WIFI connections or VPN access issues when installing access to server, CDP4-CE and domain specific software (e.g., SolidWorks).	✅ While the number of participants is usually limited by the CCDS capacity, the virtual edition had no such restrictions. The STRATHcube team involved 29 participants, 71% higher than NEACORE.	❌ A list of installation requirements had been provided one week prior, but most participants did not attempt installation until the very last day. This caused a bottleneck in terms of the help that could be provided by the event organisers and restricted time scale to find solutions.
Study	❌ Two participants had serious issues connecting to the virtual session (mostly due to poor WIFI). ❌ The size of some software files (e.g., SolidWorks) made it difficult to run on personal PCs for some participants. In such a case, a remote connection to a CCDS PC had to be established which sometimes proved to be challenging. ❌ It was more complicated to keep multiple windows open since many people had a reduced number of screens (CDP4-CE, Zoom, Slack, email, internet, domain-specific software, etc). This diminished the benefits of Zoom's share screen function which was used to present design options, proposals and presentations.	✅ Zoom breakout rooms allowed subsystems to conduct internal talks and side meetings... ❌ … but breakout rooms also isolated members from the main conversation, potentially missing out on relevant data. To compensate, each day started and ended with a design recap and an overview of each subsystem. ❌ The combination of Slack channels and Zoom chats made it sometimes hard to keep track of the information flow, particularly for people working on more than one discipline. To compensate, the three system engineers especially focused on ensuring that the information was correctly flowing in-between participants. ❌ Managing break room allocations was rather time consuming for the system engineers.	❌ The team experienced "Zoom fatigue", the weariness felt when spending many hours on a video call. ❌ Two team members did not show up for the study and remained unresponsive. Each subsystem design involved at least two participants; therefore, no subsystem was left uncovered. ❌ It was more complex to demonstrate with hands and visualise in 3D online, for instance, the classic challenge of visualising the spacecraft orientation. ❌ The lack of interactions outside of the sessions, e.g., at coffee break or lunch time, made it harder for the team to bond and connect with new team members. In addition, many participants had their video off during calls, impacting furthermore social interaction.

5. EVALUATION & REFLECTION

5.1. Discussion of Findings

Both studies achieved similar levels of requirement fulfilment. However, this evaluation parameter appeared to depend more on the mission's complexity rather than the study type. As such, a better metric for requirement fulfilment should be sought. For example, the mission could be re-evaluated against a study with a similar complexity level, for instance, with a more comparable orbit. Additionally, whilst this evaluation parameter intends to measure design quality, it cannot assure the quality of the built spacecraft model itself.

In terms of the flow of data through the server, a significant relationship was uncovered between the total number of commits per iteration and design session type. This was mostly driven by Iteration 1, despite the number of commits becoming more comparable in the following iterations. The reason for the observed difference in Iteration 1 may have been due to the increased reliance on the CDP4-CE to exchange information. In this regard, the system engineers noted a very strong initial hesitance of virtual study participants to commit data at the start of the session. However, this was resolved by emphasising the importance of communication and recommending that data is uploaded as soon as it becomes available (even if this was just a first estimation).

Both research surveys returned largely positive feedback, despite the communication issues cited. This is evidenced by the fact that not a single respondent of the first research survey scored any component of the virtual study below 'somewhat good'. Also, each respondent of the second research survey indicated that they enjoyed participating in the virtual study to varying degrees. This suggests that they felt that the adapted methodology was sufficiently applied to allow them to actively contribute to the study in a positive manner, indicating that there was no showstopping hindrances to the virtual study.

Based on the other notable observations, it was reaffirmed that communication flow was highly impacted during the virtual study. The continuous video call was expected to be used as a central hub for the team and keep participants productive/motivated. However, having different discussions on a common call was found to be impossible. Due to this, the subsystem teams spread out into several break rooms, isolating themselves from the main call. This unavoidable behaviour generated extra workload for the system engineers, who had to shift between virtual rooms to ensure that the information was flowing correctly between subsystems, thus centralising the design approach at system level.

These results suggest that the methodological adaptation was successfully applied to the virtual study despite the unprecedented challenges faced. However, it should be noted that the average age of each CE team was well below 30 years. As such, the impact of moving from a physical to a virtual study was probably limited by the fact that this age group is well-versed in digital technologies whilst the core Strathclyde CE team is not yet experienced enough to have fixed working habits.

5.2. Lessons Learned & Methods of Best Practice

Overall, the main lesson learned from this study is that a greater emphasis on the process is required in the absence of a physical CDF in order to provide satisfactory levels of support for virtual CE sessions, as shown in Figure 7. As such, with appropriate adaptation of the methodology, it is possible for CE sessions to be held virtually. However, it was found that maintaining sufficient levels of participant interaction was the greatest challenge to the virtual CE session (even though fulfilment of mission requirements did not suffer).

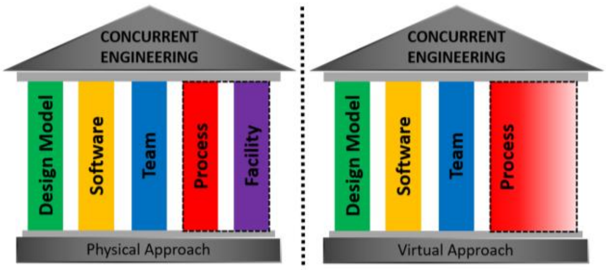

Figure 7. Basic elements of the concurrent engineering approach when applied within physical and virtual studies

Given the fact that communication is an extremely important element of the CE process, it is recommended that actions taken to reinforce team cohesion and trust are seen as a priority. Since opportunities to socialise are limited during a virtual study, such actions might include the classic tour-de-table to introduce team members which could also be prolonged with ice-breaking sessions. Additionally, the schedule could include virtual coffee breaks and participants should be encouraged to use their video, or at least add an avatar or profile picture, to make virtual interactions friendlier. Finally, the system engineers should ensure that the most appropriate and user-friendly communication platform is selected to encourage discussion before and during the CE study. This is vital for design progression and may enable the system engineers to troubleshoot other technical, procedural and behavioural issues as and when they arise.

6. CONCLUSION

This paper has synthesised the successes and challenges that arose during a virtual CE study conducted by the University of Strathclyde. It presented methods of best practice for embracing and overcoming these to provide future project teams with information that can increase the effectiveness and efficiency of virtual CE sessions and build on the experience and lessons learned from the Strathclyde team. This should simplify the future application of the practice if a scenario requiring it to be implemented ever arises again.

7. ACKNOWLEDGEMENTS

The authors would like to thank all of those involved in the NEACORE and STRATHcube design studies. This gratitude particularly extends to the participants of each research survey for their helpful feedback and responses.

8. ABBREVIATIONS & ACRONYMS

CCDS	Concurrent & Collaborative Design Studio
CDF	Concurrent Design Facility
CE	Concurrent Engineering
COVID-19	Novel Coronavirus Disease 2019
CPD4-CE	Concurrent Design & Engineering Platform 4 – Community Edition
ESA	European Space Agency
ISS	International Space Station
NEACORE	Nanospacecraft Exploration of Asteroids by Collision and Flyby Reconnaissance
OCDT	Open Concurrent Design Tool
STRATHcube	Space Debris Tracking, Re-entry Analysis and Wireless Power Transmission Student Partnership CubeSat
WPT	Wireless Power Transmission

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