Developing digital design workflow for architecture based on cleanability as a design parameter

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Abstract. This paper proposes a design approach that addresses the surface cleanability as a critical aspect of the architectural context, especially concerning the maintenance of architecture for health and hygiene purposes. The surface cleanability could be achieved through the design of surfaces in the environment where hygiene is essential. Digital design technology could contribute to the modelling, simulation and fabrication process during the development of surface forms in architecture. The study developed a digital design workflow that incorporates skeletal implicit modelling techniques as an attempt to develop the forms of surfaces. It allows the generation of a smooth and seamless surface that allows the maintenance to ensure the cleanliness of the environment. The proposed workflow also allows the iterative process to be performed between the modelling and simulation analysis to enable the evaluation of the cleanability performance of the surface. The workflow could become the basis for the development of architectural forms that appropriately address the requirement of maintenance of architectural spaces.

1. Introduction
Cleanability is vital in many architectural contexts related to health and wellbeing issues. In the domestic realm, the bathroom and kitchen have been subjected to the intensive cleaning labour to maintain its cleanliness [1]. Most of the risks in domestic and personal hygiene facilities are associated with wet surfaces such as kitchen sinks, baths, and washbasins that build up stagnant water thus act as reservoirs of the organism [2]. Public personal hygiene facilities such as bathrooms and toilets are also suffering from poor service due to the lack of cleanliness [3]. In healthcare settings, some investigations highlighted the importance of cleanable surfaces to mitigate the risk of infection transmission [4]. In public workplaces, poor building cleaning and maintenance could lead to airborne dust which can cause sick building syndrome [5].

While there is evidence showing that the cleanliness of environmental surfaces plays an essential part in its occupants’ health, the prescriptive approach in environmental control often overlook these aspects and still relies on the generic thermal, lighting, air and sound aspects [6]. The discussions on improving environmental surfaces hygiene and cleanability are barely found in architectural context. We regularly rely on the use of laborious cleaning regimes to clean our environment. Interestingly, cleaning does not always result in a positive outcome. It is found that the chemical compound inside the cleaning solution can give some adverse effects to people health [1, 6, 7, 8]. Our experience in architectural practice also much relies on common convention and intuitive approach which is seen as insufficient in achieving a cleaner architectural environment.
We argue that the way we approach cleaning issues thus needs to evolve reflecting the technological progress that we had. There was much progress we had already regarding cleaning technology. However, it is difficult to get insights into how architecture can adapt or adopt such developments. The development of the digital design process has evolved in such a way that it allows the modelling, simulation and visualisation to assess the performativity of architectural design [9]. These paper attempts to map such possibilities out of currently available literature. The study will review the available developing technologies related to cleaning and environment, then suggest the possible development direction in architecture. However, the resulted framework is still hypothetical. Therefore, further implementation is needed in the future to put the possibilities into a test.

2. The Cleaning Technologies

2.1. Self-cleaning surfaces
There were signs of progress in the development of self-cleaning surfaces in pursuit of the long-lasting, contaminant-free surfaces [10] and it is still improving its applicability. It is done by altering the physical properties surface to create a lotus effect in which the water can move freely on the top of the surface while carrying the contaminant away [10]. Many attempts at creating such surface were still struggling to maintain its hydrophobic effect over the extended period and prone to exposures and mechanical wears such as scratches and physical exposures [11, 12]. The fragility of such surfaces may suit better to protective surfaces that have a little wear and exposures but difficult to clean such as interior ceilings. The progress on the self-cleaning surface can potentially shape architectural design in which the surfaces are needed to be planned by its mechanical wear and maintenance level. It is potentially useful in the large-scale building environment such as public workplaces to increase its operational efficiency.

2.2. Automation of cleaning
The automation of the cleaning process using robots is increasing to eliminate human labour [13]. The systematic cleaning processes ensure a consistent level of cleaning, and the promise of reduced labour makes this technology inevitably appealing to people [14]. An interesting study has been conducted to see how the current domestic vacuum cleaning robot technology takes place in its real context [15]. The study found that although the robot provides ease by automating the cleaning and fulfil its function, the physical space of the house affects the way the robot used due to the limitation on the robot's locomotion. The need for flat and relatively free-obstacle floor made the users of the robot ought to change their house configuration to make the robot work sufficiently.

Cleaning technologies using pressured water has been common in industry areas mainly to remove dirt or sludge from the internal surface such as tank and vessel [16]. These technologies can be partly adapted into architectural space that is naturally wet such as bathrooms or wet toilets. It is uncommon that many public toilets suffered from poor service due to lack of maintenance. It is possible to employ waterjet cleaning technologies in such occasion to improve its services. However, the internal surfaces of the designed space need to be tailored in such a way to optimise the cleaning efficiency.

2.3. Simulation and computational modelling
The cleaning and sanitary industries also progressed in incorporating mathematical modelling from empirical observations and computer simulations [17, 18, 19, 20] to analyse and predict cleanability. The whole developments are aiming to achieve the more efficient cleaning mechanism to maintain or improve the performance of the designed system as well as reduce the needed labour to do so. Mathematical models, simulations and visualisations of cleaning processes are used to facilitate the design processes that are based on the computer-aided design by quantifying the effect of the cleaning process and predict the uncleanable features [21]. Simulations and visualisation of cleaning processes provide ground for the optimisation of the designed objects in much more efficient before prototyped into physical objects. The development of computational models and computational fluid dynamics

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(CFD) simulations to analyse and visualise cleaning process in the computer-aided design process can be extended further into architectural context in which cleanability is increasingly essential.

2.4. Digital manufacturing and construction
In architectural industry, the emerging technology in large-scale additive manufacturing enables a digital-driven construction method which allows the freedom of design, high-precision manufacturing and elimination of labour intensive moulding [22]. The use of additive manufacturing in the construction-scale industry is still immature and challenged by the limited use of materials and construction methods [23]. It required further research concerning the use of non-homogeneous material or innovative materials that exhibit essential properties for building construction such as durability, vapour imperviousness, tensile and compressive strength and low thermal expansion [24]. However, we believe that the future of the construction will advance beyond the existing construction methods. The opportunities of additive manufacturing lie in the capability of making complex geometries, no-cost individualisation, smart constructions that can adapt to environmental variations, and seamless workflow from digital design to construction [24].

The development of computer modelling techniques, computational analysis and additive manufacturing thus suggests the possibility of design workflow that enables the modelling, evaluation and fabrication of architectural design in computational medium. It is now possible to conceive design processes which enable integration of various functional requirements into one surface that tailored to specific requirements. In this study, we attempt to formulate a digital design workflow that enables quick modelling and cleanability evaluations performance. The workflow consists of iterative processes between architectural design modelling with simulation and visualisation of cleaning process which enable the ideation and evaluation of design cleanability.

3. Design Workflow Development Incorporating Skeletal Implicit Modelling

3.1. Skeletal implicit surface modelling
While the physical properties of the surfaces have significant roles in determining its cleanability, the shapes of the surfaces are also vital. Irregular surfaces such as door handles and lamp caps are found prone to the higher level of contamination and harder to clean than the regular ones [25]. However, most of the complexity of the design artefact was the result of various functional requirements which needs to be optimised. For example, the complex shape of door handles was a result of the necessity to be gripped as convenient as possible while also maintaining other requirements such as structural integrity, cost and aesthetics. Achieving cleanability thus must reflect the complex relationship between various functional requirements into one design artefact. Iterative processes become inevitable in such circumstances.

Current CAD modelling techniques are rather slow in following the iterative processes of digital design. Skeletal implicit modelling techniques enable a quick modelling of smooth, seamless surface geometry using point, line and surface primitives called skeleton [26, 27]. It works by capturing the potential surfaces that are called implicit surface from the charged primitive geometry (Fig. 1). This technique enables the creation of a manifold, smooth and seamless surface from simple points, lines and surfaces which ease the cleaning processes. The smooth blending between geometries in this technique also eliminates the cumbersome filleting procedures to create a smooth blend between two surfaces in CAD modelling process [28] (Fig. 2).

To ease the integration with the common architectural modelling technique, we use the skeletal implicit modelling add-on Cocoon to McNeel’s Grasshopper visual scripting interface for Rhinoceros developed by Stasiuk [29]. The add-on enables an easy implicit modelling in parametric environment Grasshopper thus allows parameterisation and evaluation of its geometry. We use this possibility to create a script to evaluate and visualises the resulting geometry cleanability which will be described in the next sub-section.
Figure 1. Skeletal implicit modelling techniques

Figure 2. Smooth blending between implicit geometries
3.2. Visualizing Cleanability

While the development of CFD analysis has been used to predict cleanability of a surface by measuring water-jets shear pressure level [30], its direct integration into Grasshopper parametric model still possesses many challenges. The need for a robust setup and high computational cost hinders the integration of CFD analysis in a parametric modelling environment. We tried to develop a visualisation method based on the collected empirical evidence and mathematical model as a heuristic analytical tool (Fig. 3). The script visualises the optimum cleaning effect by measuring the angle of attack and distance of water-jet from the cleaned surface. From the evidence, we had that the optimal degree of attack is approximately 75° [21]. The relation between cleaning effectiveness with the distance is decreased linearly [21]. However, we acknowledge some limitation in our assumption that needs to be detailed and clarified in the further development.

![Diagram of cleanability using water-jet from implicit surface]

**Figure 3.** Parametric modelling of cleanability using water-jet from implicit surface

The whole workflow is expected to enable a quick iterative process between the modelling and analysis of cleanability using water-jet cleaning technology within the parametric modelling environment Grasshopper. The challenge in finding an adequate mathematical model and high
computational cost for a more detailed geometry is persisting. The number of mesh faces generated from the implicit model is corresponding to the level of details that can be achieved. However, the computational cost for generating and analysing the mesh faces will increase exponentially following the increase of its number. The consistent and manifold geometry generated from the implicit surfaces is also allowing other analysis such as computational fluid dynamic (CFD) without much further adjustment. Figure 4 depicting the further possible implementation of the design process. The manifold surface from implicit modelling technique also provides easier integration to the digital fabrication process.

![Iterative Design Process](image)

**Figure 4.** The workflow of the modelling process incorporating cleanability analysis in *Grasshopper* and CFD simulation software

### 4. Conclusion

This study attempted to develop a digital design workflow within the parametric modelling platform *Grasshopper* to address the needs for cleanability. The technological development of surfaces materiality, cleaning mechanism, computer simulation and additive manufacturing open up the possibility of integration of digital workflow from design processes to the construction stage. In responding to such development, we develop the method for improving the cleanability of architectural surfaces by incorporating skeletal implicit modelling technique and cleanability assessment simulation within parametric modelling platform to enable the iterative processes between design and analysis of cleanability performance. The proposed digital workflow will enable the generation of surfaces for architectural spaces where the cleanability is essential for maintenance purposes. The use of water-jet cleaning model in our workflow suggests the potential use of this approach for designing architectural wet spaces. Furthermore, the geometry generated from implicit surface modelling are manifold which eases the integration to CFD simulation software. The further development of this workflow will address the cleanability assessment which can be done in
Grasshopper parametric environment which enables a more complex mathematical model to provide a better analysis.

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