Phygital Recycling

Development of a gamified interactive XR structure to enhance the participation of recycling

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The issue of plastic waste recycling transcends national boundaries, presenting a formidable challenge on a global scale. In Hong Kong, the endeavour to recycle plastic waste commenced in the 1980s and has undergone nearly four decades of evolution and transformation. The initial landfill-centric approach has given way to a more multifaceted and integrated waste management model. Recent years have witnessed certain communities adopting innovative joint recycling systems, which are propelled by incentive-driven mechanisms. These systems have shown initial success, yet they grapple with the challenges of low participation rates and limited reach within the populace. To amplify user engagement, gamification strategies have been incorporated into the recycling infrastructure, yielding notable efficacy in specific locales. Nevertheless, the prevailing systems predominantly rely on two-dimensional, planar interactive devices, which are beset by a paucity of informational resources and suboptimal interactivity. Immersive technologies emerge as a promising avenue to enhance the efficiency of graphical information exchange and to elevate the level of information visualization. Historical precedents indicate that immersive techniques can significantly augment user experience and bolster the propensity for repeated engagement. This study endeavours to forge an avant-garde recycling paradigm that marries the incentivizing allure of gamified reward systems with the interactive prowess of immersive technologies. It champions the adoption of a 'Phygital' system, which seamlessly melds physical and digital elements within contextually relevant environments to achieve superior outcomes. The article highlights a design framework that utilizes immersive technology to gamify recycling engagement. This framework incorporates mixed reality (MR) devices and sensors to enhance the overall experience for participants.

Keywords: *Waste Recycling, MR Interaction Design, Phygital Spatial Design, Gamification Mechanisms, Real- Virtual Connection.*

INTRODUCTION

The escalating volume of plastic waste presents a pressing global challenge. As per the 2023 data, the worldwide volume of plastic waste is projected to reach 158,943,925 tonnes, marking a 1.6% increase from 2022. In Hong Kong, plastic waste constitutes 21% of the total solid waste. The volume of plastic waste began to surge in 2021, peaking at 985,685 tonnes in 2022 (HK Environment Protection Department, 2022), thereby saturating Hong Kong's landfills. Numerous innovative methods for recycling plastic waste have been explored, with the majority of research concentrating on enhancing recycling techniques and materials. Public participation in waste management, a critical yet frequently neglected component, can significantly alleviate the challenges associated with waste recycling. In Hong Kong, government initiatives, including public education campaigns, have yielded recycling participation rates of 65% in many residential districts. The issue of residential waste recycling has garnered increasing attention, with the municipal solid waste (MSW) recycling rate reaching 32% by 2022, a 4% increase from 2020 (Lau, 2019). Despite these initial successes, there remains substantial scope for improvement. The recycling rate in many areas falls significantly below the average, and numerous residents report a lack of understanding of the existing recycling procedures in Hong Kong. Even among those who comprehend these procedures, active participation in the recycling process is often lacking. This has impeded efforts to increase the recycling rate in many areas. While most existing research has examined the relationship between the implementation of recycling policies and resident participation, few studies have focused on strategies to encourage active resident participation in plastic recycling. This study is predicated on an in-depth examination of existing gamification frameworks to develop an advanced gamification system that employs immersive technologies. The intention is to devise a mechanism that augments the community's propensity to engage in plastic recycling by instituting a series of tangible rewards and sanctions, coupled with engaging and interactive gameplay elements.

BACKGROUND

The management of plastic waste has evolved significantly since the early 20th century. Initially, discarded plastic waste was relegated to landfills. Subsequently, incineration and energy recovery methods were introduced. However, it was not until the 1970s that the concept of recycling plastics was acknowledged and implemented on a large scale (Howell, 1992). In the nascent stages, the model of plastic waste recycling was a collaborative effort between the government and businesses, with professionals hired to collect plastic waste. This method, however, proved to be inefficient.

As urbanisation progressed and community autonomy expanded, the model of plastic waste recycling evolved into a more diverse system involving government organisations, communities, and businesses. Hong Kong has adopted this model, employing a variety of methods to manage plastic waste. There are five primary types of plastic recycling methods: mechanical recycling, energy generation through direct incineration, energy generation in industrial applications, reuse in construction, and landfilling (Hou et al. 2018). Even though the most environmentally beneficial method, according to lifecycle assessment (LCA), is the Industrial Incineration approach (Hossain et al. 2021), incineration facilities capable of achieving industrial recycling will not be fully operational until 2025. Currently, the most effective method for recycling waste plastic resources is through the existing material recovery process, which includes collection, crushing, washing, melting, and recycling. Despite the presence of over 200 plastics recycling companies in Hong Kong (HK Environment Protection Department, 2022), the local recycling rate remains disappointingly low at 12.27% (HK Environment Protection Department, 2022).

One of the challenges in recycling waste plastics is that the output of secondary production is heavily reliant on the quality and quantity of the waste materials (Mehat & Kamaruddin 2011). This suggests that enhancing the separation of plastics at the source of recycling and increasing the recycling participation rate are crucial factors in improving the local plastics recycling rate in Hong Kong. In response to this, the Hong Kong government has implemented a series of measures to encourage community participation in recycling. These include the establishment of a pilot plastic waste recycling zone, the introduction of a recycling incentive system, and the promulgation of recycling policies. However, there remains significant potential for improvement in the recycling rate of plastic waste. The government's tendency to utilise top-down programmes to increase recycling (Lau, 2019) somewhat overlooks the role of individuals and communities in providing waste segregation and collection at the upstream stage of plastic recycling. Therefore, a new set of mechanisms that can integrate top-down policy requirements and be widely adopted by communities from the bottom up needs to be developed to address these issues. The comprehensive framework for gamification discussed below has the potential to significantly enhance positive engagement within the community.

Gamification mechanics

The application of gamification mechanics presents a strategic solution to contemporary issues. Gamification mechanics refer to the incorporation of game elements into non-gaming contexts or activities, offering the potential to enhance public engagement levels. The concept of utilising gamification in social development was initially proposed by Johan Huizinga, and since then, the gamification system has been extensively employed in workplace scenarios. Subsequent research has demonstrated that gamification can augment interpersonal communication, infuse enjoyment into mundane activities, increase activity participation, intensify the thrill of receiving incentives, and enhance cognitive abilities during activities (Lopez and Tucker, 2009). The integration of game mechanics has proven effective in community settings, particularly in promoting recycling behaviours (Helmefalk and Rosenlund, 2020).

Gamified mechanics are characterised by two primary features: the gamified interaction mechanism and the reward system. The former amalgamates narrative mechanics, feedback and tracking, social interaction systems, and personalised choice opportunities to deliver an immersive experience for participants. In contrast, the latter establishes clear objectives for participants through the reward system, competition and challenge mechanics, and progression and its hierarchical system, thereby increasing the likelihood of repeated engagement (Aguiar-Castillo et al., 2019). Recycling systems that incorporate gamification can optimise participant engagement in recycling plastics and encourage repeated participation.

The prevailing gamified recycling system struggles to strike an optimal balance between enhancing participation rates and maintaining user engagement through incentive policies. The "GREEN@COMMUNITY" initiative, launched by the Hong Kong Government, represents a concerted effort to facilitate community recycling. This program encompasses 40 fixed recycling convenience points and 130 mobile recycling stations distributed across Hong Kong. Participants, upon depositing recyclable materials, accrue points via the "green" mobile application, which can subsequently be redeemed for a variety of tangible rewards. This mechanism has, to a certain extent, invigorated public enthusiasm for waste recycling. However, the volume of recyclables collected remains significantly lower than the quantities amassed at neighbourhood-based recycling stations (Steuer & Chen, 2023). A critical impediment is the system's failure to engage a demographically diverse user base, attributed to its lack of entertainment value (Chan, 1998). Moreover, the monolithic point reward system fails to render the recycling process engaging or enjoyable. From a promotional perspective, the system inadequately communicates the environmental impact of users' recycling efforts, thus failing to foster long-term motivational sustainability among participants (Siu & Xiao, 2016). This deficiency undermines the effectiveness of recycling initiatives, suggesting a pressing need for an innovative game mode capable of immersing users in the otherwise mundane task of recycling. Such an approach would not only enhance the appeal of recycling activities but also serve to educate participants on the broader environmental significance of their contributions, thereby cultivating a more informed and motivated user base.

Immersive technology

The integration of immersive technology presents an effective solution to the lack of immersion in gamified recycling systems. Immersive technologies encompass Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) immersive visual technologies, which have been demonstrated to enhance user experience and engagement in various domains, such as travel (Yung and Khoo-Lattimore, 2017). Among these, MR technology effectively addresses the intangibility of digital models by facilitating interaction between digital and physical entities. MR glasses, based on this technology, provide users with a strong sense of presence through real-time interactivity and virtual system rendering capabilities. Furthermore, MR's development platform offers a plethora of input and output methods, enabling diverse interactions and providing numerous possibilities for the materialisation of digital information (Suh and Prophet, 2018). Within a gamified recycling system, the visual interaction features of the immersive system can disseminate recycling knowledge and enhance the reward mechanism. It can vividly and engagingly depict existing recycling technology solutions at the initial stage of residents' participation in waste recycling and visually display the reward system post-game participation.

A review of projects and literature reveals existing recycling game projects that apply immersive technology. Table 1 outlines the characteristics of these game systems, which can be broadly categorised into VR games using purely virtual environments and MR games with mixed virtual environments. These games significantly enhance the user's enjoyment of the rubbish recycling process and exhibit a high rate of repeat play. However, these games also exhibit some notable shortcomings. Due to their lack of connection with physical world data, most games lack a physical reward mechanism. Some games have implemented a virtual points exchange system, but the rewards and gameplay lack relevance, and the exchange of physical rewards is inconvenient. Another issue is that most games feature similar gameplay, primarily based on gesture grasping, which lacks freedom and can lead to fatigue after prolonged play. Future experiments will focus on highly personalising the gameplay and implementing a physical rewards system.

Porject	Tech	Mechanism	Pplateform
"Jede Dose	VR	accumulated	PC/VR glasses
"RecyclageVR"	MR	accumulated points	VR glasses
VeeRuby Technology	MR	accumulated points	VR glasses/mobile
Trash Time	VR	accumulated points	PC
Trash Rage VR	VR	accumulated points	VR glasses
Wasteworld	MR	accumulated points	VR glasses/mobile
Kierrätyskamut	MR	virtual prop	mobile
Recycling VR Challenge	VR	accumulated points	VR glasses

Table 1
Recycling Game Summary

METHODOLOGY

The "phygital" system is an interactive platform that amalgamates physical sensors and virtual reality technology to facilitate bidirectional real-time interaction between the virtual and real worlds. This is achieved by reading data from the physical world through sensors, thereby effectively integrating the virtual immersion of the game system with the physical feedback of the real world. In this study, a "phygital recycling" system was developed, incorporating game mechanics (Figure 1)

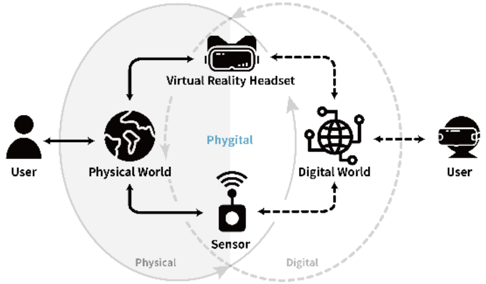

Figure 1
Some caption for the figure

At the onset of the system, plastic waste is initially collected through sensors controlled by the 'Arduino' to obtain specific waste data. This data is then analysed using a digital platform and incorporated into a highly flexible VR game. Upon completion of the game, the digital platform generates a graphic mesh file of the game's reward. Ultimately, additive manufacturing technology is employed, with a 3D printer utilising secondary materials recycled from waste plastic as the raw material for printing.

The finished print is then presented to the participant as a tangible reward for the game. The system can be broadly divided into three components: sensor-based waste data collection, the game experience facilitated by the "Unity" platform, and the tangible reward produced through 3D printing of recycled material (Figure 2).

Data collection on plastic waste

In accordance with existing plastic waste sorting regulations, seven types of plastic waste can be recycled in Hong Kong. Polyethylene terephthalate (PET) and High-Density Polyethylene (HDPE) are the most prevalent types of plastic waste in daily life and are the primary materials that the public can utilise for plastic waste recycling. Other waste types require specific recycling points for processing and are therefore not included in the scope of this study.
These two types of waste primarily consist of transparent rigid beverage bottles and non-transparent plastics. Consequently, the recycling system was designed to recycle these two types of plastic waste, PET and HDPE.
Upon disposal of plastic containers into the recycling bin, sensors within the bin initiate data collection on the waste plastics.

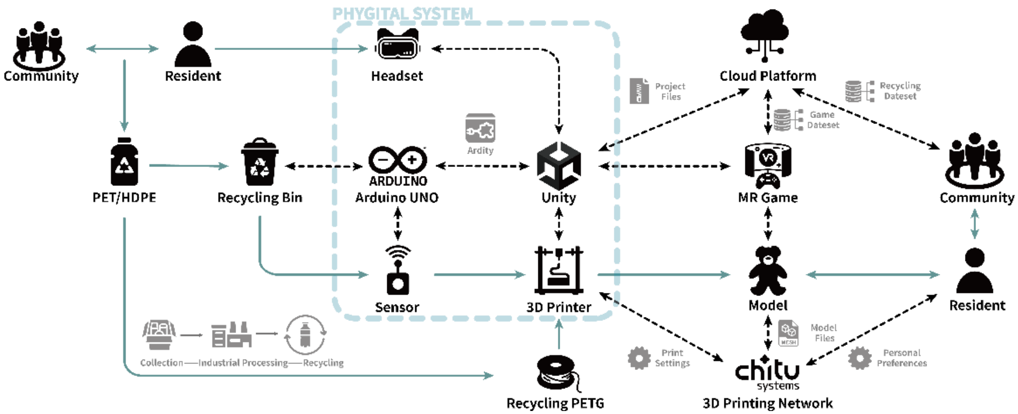

Figure 2
Recycling process based on the "Phygital" system

The "HX711" load cell module and the ultrasonic module measure the weight and volume of the waste in the recycling bin, while the "TSC230" colour sensor is utilised to determine the approximate colour of the recycled material. These sensors are strategically positioned and affixed to the recycling box. The load cell is secured to the bottom of the box, with one end attached to the box's base using nuts and bolts, and the other end connected to the weighing tray above to weigh the plastic waste. The colour sensor is affixed to
the top to measure the approximate colour of the waste inside the box, and the ultrasonic module is also secured to the top to measure the distance from the waste to the top of the box to ascertain the volume of the plastic waste (Figure 3)

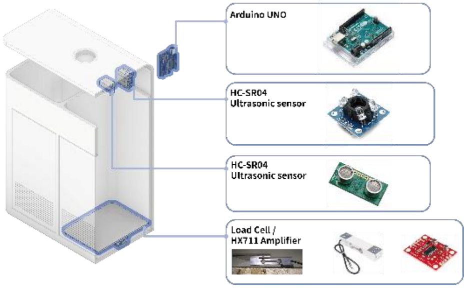

Figure 3
Recycling bins and sensors

The data from the sensors is transmitted to the "Arduino UNO" control board for processing. The "Arduino UNO" is an open-source microcontroller chip that can be programmed through the included "Arduino IDE". The current sensor data, which provides information on the weight, colour, and volume of the plastic bottles being recycled, is obtained through the IDE platform's serial monitor. Given that the "Arduino IDE" lacks the capability for graphical representation of the data, a tool is required to facilitate the transfer of the digital signals to another graphical design platform. "Ardity" is a plug-in based on Unity that reads and accesses port data to enable communication between different serial ports. By reading and writing commands from "Ardity", the sensor data can be efficiently transferred to the graphic design platform (Figure 2).

Recycling game in unity

Attributable to the comprehensive plug-in support and the sophisticated graphical interaction capabilities of the Unity platform, it was selected as the optimal digital platform for the execution of data processing and the development of a gamified recycling model. After the transmission of sensor data to Unity, a game employing Mixed Reality (MR) technology is initiated, and segmented into two distinct phases. The initial phase comprises a static graphical presentation alongside a summary of pertinent information regarding the current recycling station. Utilizing the MR device, participants are apprised of the geographical locations of proximal recycling stations, and the variety of plastics acceptable for recycling, and are provided with an intuitive representation of the aggregate number of plastic bottles that have been recycled. This is achieved through on-screen statistics, which also delineate the significant contribution of their recycling efforts towards the city's carbon emission reduction objectives (Figure 4).

Figure 4
Visual recycling interface

In the subsequent stage, the recycling system generates geometries (spheres, squares) in Unity, which correspond to the volume of secondary materials produced from the plastic waste in the recycling bins. The surfaces of these geometries are converted into a mesh using Unity's "Mesh Deformer" component, and forces are applied to certain surfaces to create a deformation effect. This effect is achieved through the use of gesture recognition scripts in the SDK component, which is equipped with two RGB colour cameras and a depth projector, thereby providing full-colour AR vision for seamless integration of virtual and physical spaces.

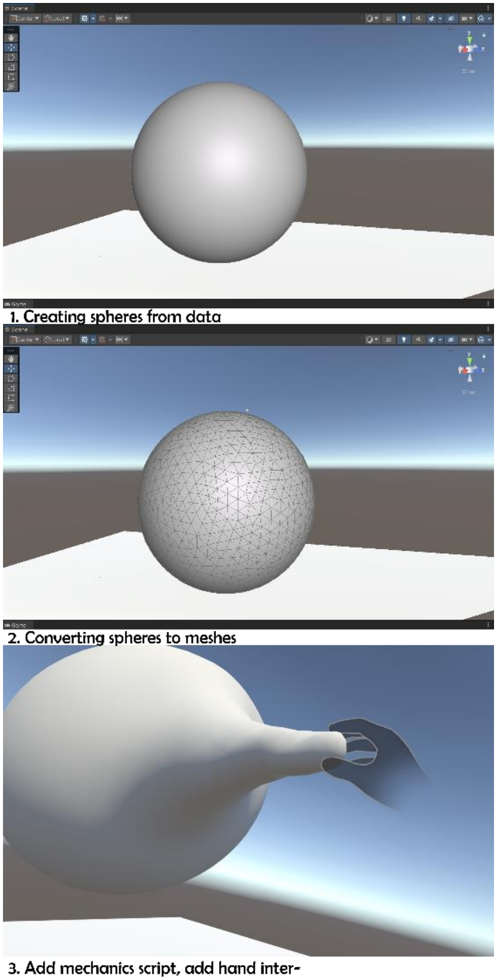

Figure 5
Games using gesture recognition technology

The "Hand Grabinteractable" component in the official SDK of the "Mate Quest3" captures the changes in real hand movements within Unity, allowing users to freely manipulate and deform the points on the surface of the geometrical objects. Through this visual AR interaction, users can customise their creations and designs according to their preferences, thereby transforming virtual recycled materials into imaginative works (Figure 5). The virtual model created can subsequently be saved in Unity and converted into an STL format file, which is compatible with the printing system of a 3D printer.

3D printing platform

The virtual models created by the participants are transferred to a networked model data platform. "Unity Cloud" facilitates online model resource management, allowing for the storage of created models in the cloud for subsequent recall and download.

In the selection of three-dimensional printing consumables, the utilization of recycled polyethene terephthalate (PET) plastic, derived from repurposed PETG plastic filaments, is employed for the fabrication of user-generated models. The PETG substrate exhibits commendable thermoplastic characteristics, boasting resilience and robustness, while maintaining its non-toxicity. Crucially, it is certified for contact with foodstuffs, underscoring its suitability for a wide range of applications (Bex et al., 2021). The material's sustainability and superior properties render it an optimal choice for three-dimensional printing endeavours. Regarding the optimization of printing parameters, the ChiTu Cloud platform offers a comprehensive solution for the enhancement of three-dimensional printing processes. This platform enables users to upload and retrieve material-specific printing parameters that are contingent upon the geometrical intricacies of the model. Additionally, the system proffers optimized support material configurations tailored to the user's model. This digital production environment is adept at providing robust technical support for three-dimensional printing activities (Figure 6).

Leveraging this technical infrastructure, a collaborative community ecosystem centred on recycling initiatives has been established. Within this community, a synergistic relationship is fostered among participants, game developers, and material scientists, all of whom are engaged in the continuous optimization and refinement of processes within a unified system. Following the release of a game prototype by developers, community participants can contribute gameplay data and generate model resources. Concurrently, developers specializing in recycling materials can iteratively fine-tune the parameters for PETG materials within the three-dimensional printers, in response to the varying requirements of different models. Ultimately, this community-driven and Phygital recycling system achieves a harmonious alignment, characterized by its self-sustaining and self-optimizing nature. The model demonstrates the potential for replication across diverse regional communities, thereby promoting a scalable and sustainable approach to three-dimensional printing and recycling practices.

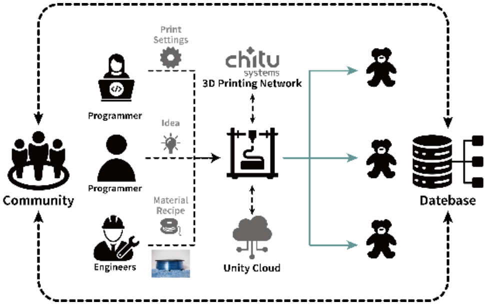

Figure 6
Additive manufacturing-based recycling networks

DISCUSSION AND CONCLUSION

The system ingeniously melds gamification mechanisms with immersive technology, elevating the plastic waste recycling experience to unprecedented heights. Through the integration of a digital twin system, participants are afforded a novel experience of transforming plastic waste into digital assets. As the deployment of immersive technology and equipment extends to the community, it is anticipated that the system will garner increased participation from community members. This, in turn, is expected to catalyze the popularization of recycling concepts and enhance recycling rates through the facilitation of repeated experiential learning.

When juxtaposed with conventional recycling systems, the game mode augmented by immersive technologies elevates the user experience to unprecedented heights. Through the incorporation of gesture recognition and virtual reality (VR) technologies, the erstwhile mundane task of waste recycling is transformed into an innovative and creative endeavour. This approach is manifestly more engaging than simplistic point exchange systems. Through iterative participation, the ethos of plastic waste recycling is poised to gain traction and potentially integrate into the quotidian practices of community residents.

With respect to the reward mechanism, the system eschews a virtual points-based approach in favour of actualizing the gaming experience through the application of additive manufacturing technology. Tangible rewards have been demonstrated to possess greater allure compared to virtual counterparts. The utilization of PETG consumables concurrently amplifies the demand for the output of local recycling enterprises, thereby addressing the issue of market availability for secondary materials to a certain degree.

In culmination, the system, in synergy with cloud data technology, aggregates user recycling behaviours and philosophies. This data repository can be collaboratively analysed and refined with technical experts to facilitate dynamic updates. This process not only yields invaluable empirical insights in the realms of additive manufacturing and game design but also contributes foundational data to inform the evolution of local recycling initiatives. Moreover, the replicability of this model is instrumental in disseminating recycling principles and catalysing an increase in plastic waste recycling rates within communities.

However, the experiment also has room for improvement. Firstly, the system has not undergone comprehensive process testing. Although various technological components have been tested by the team in other projects, particularly the "Phygital" system that interacts with sensors and MR devices, further testing is required. In a previous research project, researchers assisted laypeople in constructing complex architectural models using a physical device embedded with sensors (Figure 7). The results were promising, as laypeople were able to construct complex columns using gesture interaction with the aid of the MR device. However, the noise and accuracy of the sensors within the system, as well as those in the rubbish bin, need to be tested. Another consideration is the experimental site and evaluation. Although the study planned a community-based plastic waste recycling system, further thought needs to be given to specific recycling areas and locations within the community. The method of conducting a step-by-step evaluation based on recycling data from different areas following the implementation of the recycling programme also needs to be explored

In conclusion, this research introduces an innovative recycling model that synergistically integrates gamification systems, immersive technologies, and sensor applications to realize a digital twin. The disparate technologies within this framework are cohesively unified and integrated within the Unity engine, facilitating multimodal collaborative efforts. Looking forward, this model harbours the capacity to assimilate additional community feedback, thereby fostering participatory design in the outreach initiatives. Furthermore, the outcomes of recycling endeavours can be digitised and leveraged as digital assets, serving to underscore the achievements of community recycling efforts. This approach not only enhances the efficiency and effectiveness of recycling processes but also promotes greater community engagement and environmental stewardship.

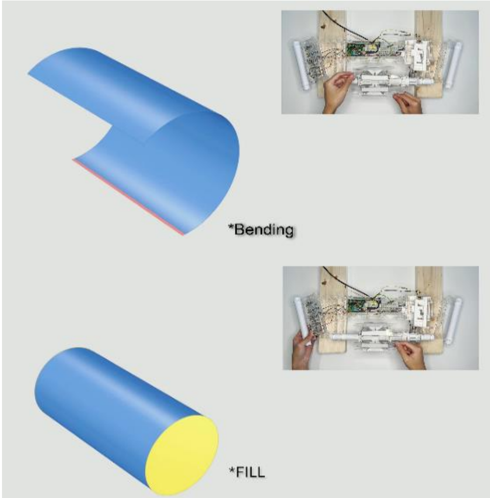

Figure 7
“Phygital” modelling system

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REFERENCES

Aguiar-Castillo, L., Clavijo-Rodriguez, A., De Saa-Perez, P., Perez-Jimenez, R., 2019. Gamification as An Approach to Promote Tourist Recycling Behavior. Sustainability 11, 2201. https://doi.org/10.3390/su11082201

Bex, G.J.P., Ingenhut, B.L.J., ten Cate, T., Sezen, M., Ozkoc, G., 2021. Sustainable approach to produce 3D-printed continuous carbon fiber composites: “A comparison of virgin and recycled PETG.” Polymer Composites 42, 4253–4264. https://doi.org/10.1002/pc.26143

Chan, K., 1998. Mass communication and pro environmental behaviour: Waste recycling in Hong Kong. Journal of Environmental Management 52, 317–325. https://doi.org/10.1006/jema.1998.0189

Helmefalk, M., Rosenlund, J., 2020. Make Waste Fun Again! A Gamification Approach to Recycling, in: Brooks, A., Brooks, E.I. (Eds.), Interactivity, Game Creation, Design, Learning, and Innovation. Springer International Publishing, Cham, pp. 415–426. https://doi.org/10.1007/978-3-030-53294-9_30

Hossain, Md.U., Ng, S.T., Dong, Y., Amor, B., 2021. Strategies for mitigating plastic wastes management problem: A lifecycle assessment study in Hong Kong. Waste Management 131, 412–422. https://doi.org/10.1016/j.wasman.2021.06.030

Hou, P., Xu, Y., Taiebat, M., Lastoskie, C., Miller, S.A., Xu, M., 2018. Life cycle assessment of end-of-life treatments for plastic film waste. Journal of Cleaner Production 201, 1052–1060. https://doi.org/10.1016/j.jclepro.2018.07.278

Howell, S.G., 1992. A ten year review of plastics recycling. Journal of Hazardous Materials, Waste Minimization 29, 143–164. https://doi.org/10.1016/0304-3894(92)85066-A

Environmental Protection Department, Hong Kong SAR Government. (2022). Hong Kong Collector / Recycler Directory. Retrieved from https://www.wastereduction.gov.hk/en-hk/industry-support/hong-kong-collector-recycler-directory.

Environmental Protection Department, Hong Kong SAR Government. (2022). Monitoring of solid waste in Hong Kong—Waste statistics for 2010. Retrieved from https://www.wastereduction.gov.hk/sites/default/files/resources_centre/waste_statistics/msw2022_eng.pdf.

Lau, E.C.F., 2019. Hong Kong Needs to Embrace a Holistic Approach to Waste Management, in: So, W.W.M., Chow, C.F., Lee, J.C.K. (Eds.), Environmental Sustainability and Education for Waste Management: Implications for Policy and Practice. Springer, Singapore, pp. 73–97. https://doi.org/10.1007/978-981-13-9173-6_6

Lopez, C.E., Tucker, C.S., 2019. The effects of player type on performance: A gamification case study. Computers in Human Behavior 91, 333–345. https://doi.org/10.1016/j.chb.2018.10.005

Mehat, N.M., Kamaruddin, S., 2011. Optimization of mechanical properties of recycled plastic products via optimal processing parameters using the Taguchi method. Journal of Materials Processing Technology 211, 1989–1994. https://doi.org/10.1016/j.jmatprotec.2011.06.014

Siu, K.W.M., Xiao, J.X., 2016. Design and management of recycling facilities for household and community recycling participation. Facilities 34, 350–374. https://doi.org/10.1108/F-08-2014-0064

Steuer, B., Chen, P., 2023. Exploring capacities, environmental benefits and potential for a circular economy on waste plastic bottles in Hong Kong. Resources, Conservation and Recycling 199, 107270. https://doi.org/10.1016/j.resconrec.2023.107270

Suh, A., Prophet, J., 2018. The state of immersive technology research: A literature analysis. Computers in Human Behavior 86, 77–90. https://doi.org/10.1016/j.chb.2018.04.019

Yung, R., Khoo-Lattimore, C., 2017. New realities: a systematic literature review on virtual reality and augmented reality in tourism research. Current Issues in Tourism 22, 1–26. https://doi.org/10.1080/13683500.2017.1417359 (Accessed: 8 February 2022)