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Frugal Education: What, why, and how?

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Abstract

This paper explores how frugal innovation practices can challenge resource constraints by leveraging available resources in creative and innovative ways towards more affordable, practical, sustainable and resilient education practice. The education sector has faced many challenges when adapting practice to deliver quality education in the wake of a world-changing pandemic. There is a great deal we can learn from each other with regards to the frugal application of resources, such as time, money, people and space. However, forms of frugality in education design are driven by necessity and are reactive as opposed to proactive measures. We can, however, learn from educators and institutions that have been able to achieve significant educational impact at low cost with far fewer resources, adopting frugal approaches to education design and delivery. This paper proposes a set of frugal education aspects that demonstrate how frugal design practices can be organised and applied within an educational context. The aspects are outlined, and examples are presented to illustrate their effectiveness within existing education practice. This paper seeks to contribute to the existing knowledge base and research into frugal innovation practice as it applies within an education context, reframing the use of the term 'frugal' away from affordability and poor quality, towards a more expansive understanding that establishes a foundation on which to build, define, and contextualise frugality within an education context. The paper concludes with recommendations for the development of practical resources, informed by the research, to support educators in the design of frugal education practice.

KEYWORDS
education design, frugal education, innovation, sustainability, sustainable education

1 | INTRODUCTION

It is not uncommon to see frugality in education. Frugal characteristics can be found within learning environments across the world (Jackson et al., 2020; Radjou et al., 2012; Toyin Ojo et al., 2022). Examples of frugal practice include utilising equipment donated or passed down from one business or individual to another (e.g. Streicher-Porte et al., 2009); digitising learning materials to reduce costs (e.g. Haleem et al., 2022); re-purposing underutilised spaces to create multi-use educational environments (e.g. Locicero & Trotz, 2018; Hoang et al., 2023; Tan et al., 2023); and the recycling of low-cost materials as teaching and learning resources (e.g. Fadhli et al., 2023; Minoi et al., 2023). These are all examples of frugal practice, and all serve a valuable purpose. However, these forms of frugality are commonly driven by necessity and are reactive measures taken in response to a problem or a situation that has already arisen, as opposed to proactive measures, that are taken in anticipation of a problem or situation. Both reactive and proactive measures are essential for addressing problems and risks in academic contexts. While reactive measures can help mitigate the negative consequences of existing practice, proactive measures can help mitigate against the excessive and unsustainable consumption of finite resources.

On top of the challenges already faced by education, the COVID-19 pandemic has strained existing practices and infrastructure. One widespread example being the rapid transition to remote and online education provision needed in the wake of large-scale lockdowns and social distancing practices (Meinck et al., 2022; Reuge et al., 2021). This has had a profound and lasting effect, not only on existing education practice (Sharma & Shree, 2023; Tang, 2022) but also on the sustainability of future education provision (de Wit & Altbach, 2023; Meinck et al., 2022), further exacerbating socioeconomic inequality globally (Bonal & González, 2020; Gee et al., 2023; Zancajo, 2020). As all educators have faced the challenge of adapting their practice to deliver quality education in the wake of a world-changing pandemic (Onyema et al., 2020; Reuge et al., 2021), there are increasing opportunities to learn from each other with regards to the frugal use of resources, such as time, money, people and space.

The term 'frugal' is often represented in the vernacular as meaning cheap (Brem, 2017), and mainly in reference to money, rather than as the quality of being economical with the consumption of resources, in whatever form they might take. However, perceptions are shifting from cheap to resourceful, as frugal practices are seen as effective methods for delivering more 'responsible innovation' (Brem, 2017, p. 39) and addressing global Sustainable Development Goals (United Nations, 2019) towards a more sustainable future.

This makes frugal approaches important for promoting education practices that are inclusive, accessible and environmentally conscious, particularly in ensuring that quality education is both affordable and sustainable on a global scale. Investments required to respond to the rising cost of education present risks of further increasing the disparity between educational practice in the Global North and Global South (Rubin & Fleisch, 2018). Educators the world over need to leverage available resources in innovative ways to deliver high-quality educational experiences with minimal resource costs. This provides an opportunity to identify and learn from educators and institutions that have been able to achieve significant educational impact with far fewer resources, adopting a frugal approach to education design and delivery. Examples include Arvind Gupta's 'Toys from Trash' (e.g. Gupta, 2013); frugal science practice using Foldscopes (e.g. Jackson et al., 2020); repurposing flatbed scanners to affordably image large interference and diffraction patterns in two dimensions (e.g. Koopman & Gopal, 2017); and frugal engineering experiments using remote, low-cost, open-source laboratory installations (e.g. Reid et al., 2022).

Frugal approaches to education will become increasingly important as educators, and their respective institutions, respond to environmental, cultural and socio-economic factors that constrain the availability of resources. Such constraints have the potential to act as a catalyst for creativity and entrepreneurship within education (Haught-Tromp, 2017; Mehta & Zhu, 2016; Toyin Ojo

et al., 2022). This paper will explore how frugal approaches can challenge resource constraints by leveraging whatever resources are available in creative and innovative ways towards the design of more affordable, practical, sustainable and resilient education practice.

The next section will discuss the multifaceted concept of Frugal Innovation, which manifests across various cultures and has been pivotal in addressing complex problems by creatively utilising limited resources. It explores how this approach, traditionally applied in engineering and design to foster scalable and sustainable solutions, is increasingly relevant to educational innovation, potentially offering pathways to more inclusive, resource-efficient and environmentally conscious educational practices. The section will delve into the integration of frugal innovation approaches within educational design, highlighting how such approaches can significantly enhance learning outcomes through resourceful and sustainable methods. It will explore various examples of frugal education in action, from MOOCs (Massive Open Online Courses) designed for refugee learners to inventive uses of low-cost materials in STEM (Science, technology, engineering and mathematics) education, demonstrating the potential for frugal approaches to create impactful, accessible and high-quality education across diverse settings.

2 | FRUGAL INNOVATION

The concept of *Frugal Innovation* can be found in many different cultures under differing colloquialisms, depending on the country in question. Examples include *Jugaad* or *Jugaar* in Hindi, which roughly translates to innovative fix (Radjou et al., 2012); *Gambiarra* in Brazil, referring to a workaround (Radjou et al., 2012); *Bricolage* in France, which is akin to tinkering (Soni & Krishnan, 2014); *D.I.Y*, an acronym for do it yourself; and *Disruptive Innovation*, whereby a new idea or approach disrupts and existing market (Radjou & Prabhu, 2015). Each term, despite its unique cultural origin, embodies the essence of what is referred to generally as frugal innovation. The term means to creatively improvise solutions to problems utilising limited resources. To hack together, make do or develop a practical workaround to a specific problem. Individuals and organisations in countries such as Brazil, Russia, India and China, known under the grouping acronym as BRIC economies (O'Neill, 2001; Radjou et al., 2012), as well as many other developing populations, have embraced existing technological, environmental, financial, temporal and spatial constraints in frugal ways to create innovative solutions to complex problems.

Frugal can often be misconstrued as low-quality, or something that lacks depth, due to perceptions of cost saving as a reductive process. However, through the growing popularity of frugal innovation, the term is evolving from the past Oxford English Dictionary definition of 'sparing or economical as regards money or food' (Oxford English Dictionary, 2011) to include other resource types, such as time, physical and virtual space, accessibility and environmental resources (Soni & Krishnan, 2014). The definition has since changed to define frugal as 'careful or sparing in the use of food, goods, etc.; economical' (Oxford English Dictionary, 2023). The term Frugal Innovation has been adopted in many fields to describe changes in practice using resource-effective methods (Prabhu & Jain, 2015). Repurposing tools and techniques from disparate disciplines, industries and environments to solve problems in ways that are not usually considered through traditional or existing methods.

Frugal Innovation, within the context of design, engineering and creative thinking, has yielded scalable and sustainable results for complex problem-solving within developing countries (Zeschky et al., 2011). Such practice is revolutionising global innovation in sectors beyond engineering and design (Radjou & Prabhu, 2015). The concept of frugal innovation is widely recognised within industry, in no small part through the pursuit of commercial opportunities within developing countries that provide a fertile landscape for business growth. The acquisition of new low-end consumers provides an opportunity to grow brand recognition and loyalty within the nascent middle class of emerging markets (López-Sánchez & Santos-Vijande, 2022).

Whether designing the world's most affordable car in India (e.g. Bhatti, 2012) or providing mobile banking in Kenya (e.g. Radjou et al., 2012), this disruptive frugal approach to innovation is revolutionising industries, and therefore, might similarly present an opportunity to positively impact education innovation. This phenomenon has only increased in popularity in recent years, with many large manufacturing and product design companies adopting a frugal engineering mindset to deliver safe, affordable and scalable transportation, healthcare and housing solutions (Radjou & Prabhu, 2015; Radjou et al., 2012). Initially addressing the needs of developing countries, this creative problem-solving approach is now having an impact in developed nations (Winkler et al., 2020) through phenomena such as the sharing economy, exemplified by the likes of Airbnb and Uber, as well as maker movements like FabLabs and Hackerspaces (e.g. Prabhu, 2017), demonstrating an increasing appetite for affordable and sustainable innovations.

It is important to note that frugal innovation practices, however economically sustainable, do not necessarily positively impact the environment (Albert, 2019). By incorporating environmentally conscious models such as doughnut economics (Raworth, 2012) and the circular economy (Stahel, 1982, 2016), combined with inclusive and equitable open education practices (UNESCO, 2019), there is the potential to enhance environmental sustainability using sustainable frugal innovation methods and the open sharing of sustainable practices to the benefit of both society and the natural world. The rising cost of materials, scarcity of resources, environmental impact considerations and a culture-shift towards conscious consumerism (Yarimoglu & Binboga, 2019) is highlighting sustainability, cost-saving and efficiency challenges worldwide. These factors pose a challenge to the delivery of services in a sustainable and cost-effective manner, and a similar set of challenges now faces the education sector.

3 | OPPORTUNITIES FOR FRUGAL APPROACHES WITHIN EDUCATION

There is sufficient scope for education institutions to better leverage existing resources at the speed of need, such as time, money, people and space, by applying frugal aspects to new and existing pedagogical practice. Doing more with less — the essence of frugal innovation. Many educators and learners have already embraced frugal approaches to great success, for example, teaching frugal science lessons using Foldscopes; low-cost origami-inspired paper microscopes for use in STEM education (e.g. Jackson et al., 2020); and repurposing a dilapidated university shuttle bus into a mobile playful-STEM lab for Malaysian schoolchildren, co-created with students at Universiti Malaysia Sarawak (UNIMAS) (e.g. Tan et al., 2023). These examples demonstrate available opportunities for applying frugal methods and practices in an education setting to deliver high-quality, sustainable and positively disruptive education across all nations, irrespective of wealth, population size or global standing.

One aspect of education that could benefit from a frugal innovation approach is learning design. Learning design refers to the process of structuring educational experiences to achieve specific learning outcomes. It involves planning, developing and organising curriculum and resources to effectively guide the students' learning journey. This process considers various elements such as learning objectives, content delivery methods, assessment techniques and the use of technology, ensuring that the educational experiences are engaging, accessible and appropriate for the intended audience.

From the production of learning materials to the administration of courses and assessment, there are many opportunities to re-engineer existing learning designs by approaching them with a frugal mindset. Shah and Santandreu Calonge (2019) provide an example of this concept through their development of a frugal MOOC, focusing on learner needs, content customisation, local stakeholder engagement, technological infrastructure and green mobile-enabled technologies. This learning design is specifically engineered to overcome the barriers that prevent refugee learners from

accessing and participating in education. 'It is only through a reconceptualization of MOOCs design, through taking on a frugal approach that is adaptable and contextualized, that the existing barriers of online education can be opened' (Shah & Santandreu Calonge, 2019, p. 13). Whether designing a module, delivering a lecture or developing resources for online students, a frugal approach to educational design and innovation could positively impact the education sector and lead to transferability into wider society through exposure to new practices and sustainable approaches, potentially fostering the acquisition of creative problem-solving skills.

As Leadbeater describes it, 'the opportunities for lean and frugal innovation in education are so large because the waste of talent is so immense. That is propelling innovators and social entrepreneurs all over the developing world to find better, lower-cost ways to educate millions of people on only very modest incomes at high quality' (Leadbeater, 2014, p. 71). The leaner the practice, the more feasible it will be to produce, deliver and be replicated by others. Examples of lean practice can be observed within engineering, such as the Tata Ace, a small truck designed to be affordable and robust yet costing 50% of the price of existing commercial vehicles. 'The Ace was developed with a minimal budget and a team of five designers, a fraction of what traditional car makers would spend' (Leadbeater, 2014, p. 71). Drawing from Leadbeater's insights on frugal innovation in industry, the development of the Tata Ace exemplifies how lean practices can dramatically reduce costs while maintaining high quality and robustness. This principle, when applied to education, suggests that adopting lean and frugal methodologies could similarly transform educational practices. By focusing on essential learning outcomes and leveraging cost-effective resources, educators can deliver high-quality education that is both accessible and scalable, mirroring the efficiency seen in engineering innovations like the Tata Ace.

This mindset of utilising what is already available and focusing on essentials to maximise efficiency and effectiveness in education leads us to reassess the role of technology in innovative learning environments. While technology certainly plays a significant role in education innovation, it is important to recognise that innovation is not exclusively limited to the integration of cutting-edge tools and platforms. Teaching and learning innovations, particularly within the higher education (HE) sector, have a tendency to focus on the adoption of cutting-edge technologies and trending instructional strategies as a means to enhance the quality of teaching and learning. Examples include virtual, augmented and mixed reality experiences (e.g. Martín-Gutiérrez et al., 2017); MOOCs (e.g. Zemsky, 2014); and flipped learning approaches (e.g. O'Flaherty & Phillips, 2015). These strategies and large-scale infrastructure investments are seen as powerful tools in the arsenal of modern higher education institutions (HEIs). However, they are not a panacea for addressing persistent structural issues such as inequalities in student experience, engagement and attainment (Davis, 2017) and should therefore not take precedent over innovative practice that leverages existing technologies in creative ways.

Instead of relying on new technologies, business strategies or infrastructure developments to inform the next big leaps in education innovation, educators could look to better utilise trailing-edge technologies (Groom, 2013; Udell, 2013), strip back existing strategies to their essential components and explore the use of existing infrastructure in creative ways to better serve the student as paramount. For instance, the incorporation of game-based learning principles into analogue STEM activities in rural Malaysia to teach computational thinking where access to digital technology is largely inaccessible (e.g. Mohamad et al., 2019), or the use of peer-to-peer learning models such as virtual educational escape rooms built in Microsoft Teams to foster collaboration and knowledge sharing when physical interaction is not possible (e.g. Arnab, Eyre, et al., 2021), in this instance using the tools available in response to the COVID-19 pandemic lockdowns. These instances illustrate pedagogical innovation that transcends the pursuit of the latest technological advancements, opting instead to ingeniously repurpose existing technologies to overcome resource limitations. This approach showcases a versatile application of technology, where innovation stems from creative problem-solving within existing means.

As Arnab (2020) describes within the context of game-based learning, educators should not be driven solely by the affordances of new technologies for their own sake, but instead pragmatically and holistically, adopting the most suitable and practical technologies at the speed of need, thereby enabling educators to build flexible and reconfigurable learning designs in response to the beneficiary's needs, as and when they arise. Investments in emerging technologies and strategies are important for innovation within education practice, but they can also come at a great cost, both in time and money. If such investments are not leveraged effectively to enhance learning, alleviate resource costs and improve the sustainability of teaching practice, they can lead to reduced impact and, as a consequence, may result in additional resource costs through remedial action to adapt and replace ineffective initiatives further down the line. Therefore, by exploring existing cultural, environmental and technological education practice through the lens of frugal innovation, there is an opportunity to establish an education-centric approach to frugal innovation to help address these persistent structural and environmental issues in sustainable ways.

4 | TOWARDS FRUGAL EDUCATION ASPECTS

As (Rao, 2013, p. 66) describes, 'the adoption of frugality entails design principles that advocate minimal use of re-sources for realising efficient functioning of products'. A set of guiding principles, encapsulating key frugal aspects, could perform a similar function within an educational context towards fostering creativity, conscious resource consumption and greater environmental and practical sustainability. An initial set of principles was developed and subsequently applied within a game-based learning design project at Coventry University (e.g. Clarke et al., 2020). Successive iterations introduced more detailed categorisation in the form of frugal aspects, proving effective for mapping on a more granular level, using specific aspects to articulate the frugal practices within a given learning design (Arnab, Mahon, et al., 2021). Consequently, a set of nine frugal education aspects — organised under three guiding principles — has been proposed, advocating for the use of frugal considerations in learning and teaching design, see Figure 1. These frugal education aspects have been inspired by examples of frugal innovation practice within industry and informed by frugal initiatives within the education sector. Accompanying each aspect is a list of considerations and characteristics that have been synthesised from the source material.

Each consideration can be used as a prompt to incorporate frugal approaches into new and existing education designs. For example, to encourage resourcefulness, one consideration might be to *recycle, upcycle and combine materials and trailing-edge technologies in new and inventive ways, extracting untapped value and extending their lifespan*. These characteristics further distil insights from the source material and helped define each aspect. The characteristics can be used to identify frugal approaches within a chosen design. For example, the presence of characteristics such as to *improvise*, *recycle*, *repurpose* or *hack* can be used as indicators of resourcefulness. While non-exhaustive, each list of characteristics can serve as a valuable aid for identifying frugal practice and will provide a basis for the development of practical resources for frugal education design.

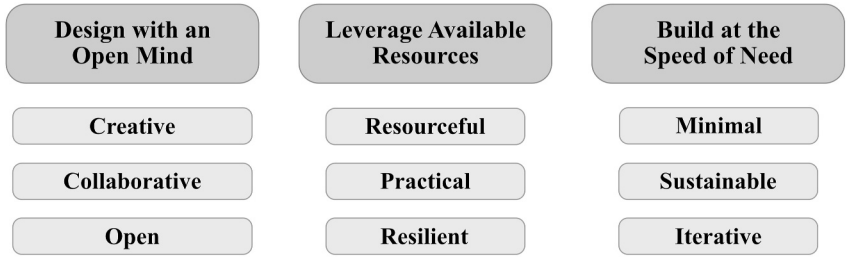

FIGURE 1 Frugal education aspects; organised under the three guiding principles.

4.1 | Design with an open mind

This first principle advocates for the use of creativity, collaboration and openness within a frugal education design process. These aspects can be found within a variety of frugal approaches.

The source material surfaced key aspects of design from the perspective of frugality, including *creativity*, which is an essential aspect of any design process. Identifying and addressing constraints through creative problem-solving leads to novel solutions, as identified within existing frugal innovation practice (Radjou & Prabhu, 2015). This is especially effective when collaborating with others to solve a collective problem. *Collaboration* and co-creation with stakeholders can provide valuable insights and perspectives early in the design process, as evidenced within the Google Ventures SPRINT process (Knapp et al., 2016) and expended upon by Coventry University's Disruptive Media Learning Lab through the CU course and module design sprints (Richards et al., 2017, 2019). *Open* practice, such as sharing designs under Creative Commons licencing (Creative Commons, 2023), can foster sustainable and democratised innovation and knowledge sharing in education. By allowing educators and their students to access, remix, and build upon existing resources, a circular economy of open educational practice can be cultivated, facilitating the implementation and adaptation of sustainable educational designs.

Please refer to Table 1 for a breakdown of each aspect, its respective characteristics and considerations and the key source materials that provide a rationale for their inclusion.

4.2 | Leverage available resources

This second principle advocates for the use of resourcefulness, practicality and resilience within a frugal education design process.

Resourceful design from a frugal perspective can manifest in a variety of ways including through the recycling, upcycling and repurposing of pre-existing and readily available materials and resources. This is a recurring theme found within frugal innovation practice and can easily be applied in an educational context. Examples of which can be seen within the ACES international research project in Malaysia, Indonesia and Vietnam. Educators in Malaysia repurposed a decommissioned university shuttle bus, converting it into a mobile playful STEM lab, complete with solar power generation and rainwater harvesting, that can be transported to rural communities who lack access to the kinds of teaching facilities that are made available on the bus (e.g. Tan et al., 2023).

ACES partners in Indonesia adapted the CreativeCulture STEMBucket concept (Minoi et al., 2023), designed and developed by educators in Malaysia, for application in schools across Indonesia. STEMBucket: Indonesia encourages STEM learning through playful and frugal activities, utilising inexpensive tools and everyday household objects to create engaging STEM-based projects for school children (e.g. Fadhli et al., 2023). The STEMBucket content changes iteratively as each new set of students sustainably sources additional materials and resources from their local environment to add to the STEMBucket to help aid them in creating new solutions to problems posed within a given STEMBucket activity. All three of the above examples are *resilient* in their design and can be reconfigured, scaled and adapted in response to changing conditions and the availability of materials and resources.

The Hasso Plattner Institute of Design at Stanford University, more often referred to as 'd.school', developed a set of tools, templates, insights and guidance for developing creative and *practical* spaces, based on their experience operating and adapting their design thinking institute over several years. Using raw materials and repurposing existing resources in creative ways, the multidisciplinary team at d.school was able to construct dynamic teaching and learning spaces at a fraction of the resource cost of traditional classroom environments (Doorley & Witthoft, 2011). The Stanford d.school is an exemplar of frugal practice in education and demonstrates all nine of the proposed aspects in abundance.

TABLE 1 Design with an open mind: Proposed aspects, characteristics and considerations; linked to their respective source materials.

Aspects and characteristics	Considerations	Source material
Creative • Inventive • Open-minded • Innovative • Experimental • Imaginative • Novel	• Seek inspiration from disparate sources • Combine ideas, techniques and concepts from different disciplines in innovative ways • Foster experimentation, creative thinking and problem-solving within your participants • Incorporate insights from participants into future design iterations	• CreativeCulture (Arnab et al., 2019; *CreativeCulture*, 2019) • CU SPRINT/Micro SPRINT (Richards et al., 2017, 2019) • DS106 (Groom, 2013; Groom & Burtis, 2010) • Fab Lab (Fleischmann et al., 2016; The Fab Foundation, 2024) • Frugal Innovation (Radjou & Prabhu, 2015) • GameChangers (Arnab et al., 2017; GameChangers, 2024) • Jugaad Innovation (Prabhu & Jain, 2015; Radjou et al., 2012) • Make Space (Doorley & Witthoft, 2011) • SPRINT (Knapp et al., 2016) • Toys from Trash (Gupta, 2013) • Trailing-edge Technologies (Groom, 2013; Udell, 2013)
Collaborative • Co-creation • Cooperation • Collaboration • Teamwork • Receptiveness • Inclusivity • Empathy	• Great learning design is achieved through collaboration • Include your audience in the design process; the earlier the better • Listen to your audience • Encourage audience participation • Be empathetic to audience needs, concerns and suggestions for improvement • Use what you learn to co-create the learning design with those it is designed to serve	• CreativeCulture (Arnab et al., 2019; *CreativeCulture*, 2019) • CU SPRINT/Micro SPRINT (Richards et al., 2017, 2019) • DS106 (Groom, 2013; Groom & Burtis, 2010) • Fab Lab (Fleischmann et al., 2016; The Fab Foundation, 2024) • Frugal Innovation (Radjou & Prabhu, 2015) • GameChangers (Arnab et al., 2017; GameChangers, 2024) • Kotoba Miners (York, 2014) • SPRINT (Knapp et al., 2016) • UK Government Design Principles (GOV.UK, 2019)
Open • Open access • Openly licenced • Free to use • Remixable • Open source • Shareable • Universal design • Knowledge sharing • Transparency • Openness to new ideas • Open Educational Resources (OER)	• Share your designs by making them freely available within the public • Allow others to apply, adapt and build upon your work through clear and detailed guidance • Make your designs easily discoverable, accessible and openly licenced through Creative Commons • Iterate in public and crowdsource ideas through open and collaborative design and development practices	• CC Licencing (Creative Commons, 2023) • CU SPRINT/Micro SPRINT (Richards et al., 2017, 2019) • DS106 (Groom, 2013; Groom & Burtis, 2010) • GameChangers (Arnab et al., 2017; GameChangers, 2024) • Make Space (Doorley & Witthoft, 2011) • Models for Sustainable OERs (Downes, 2007) • OER Commons (OER Commons, 2023)

TABLE 1 (Continued)

Aspects and characteristics	Considerations	Source material
• Open Education Practice		• Recommendation on OERs (UNESCO, 2019) • Show Your Work! (Kleon, 2014) • Toys from Trash (Gupta, 2013) • UK Government Design Principles (GOV.UK, 2019)

Please refer to Table 2 for a breakdown of each aspect, its respective characteristics and considerations and the key source materials that provide a rationale for their inclusion.

4.3 | Build at the speed of need

This third and final principle advocates for the use of minimalism, sustainability and iteration within a frugal education design process.

The GameChangers initiative, first established at Coventry University's Disruptive Media Learning Lab, is a team of practice-based researchers, designers and technologists that focus on the design and implementation of playful and gameful learning experiences (Arnab et al., 2017; GameChangers, 2024). The team practices a minimum viable pedagogy approach to learning design through rapid prototyping, testing and iteration at the speed of need. This *minimalist* approach is applied most often to GameChangers projects and activities through the KISS principle, an acronym for 'keep it simple and straightforward', which substitutes the unnecessary term *stupid* with the more suitable and appropriate *straightforward*. Adopting a minimalist mindset allows the team to work at an accelerated pace, to quickly identify effective strategies and areas in need of improvement. This approach ensures resources are used efficiently, keeping the team agile and focused on refining aspects of the learning design that demand more attention.

Sustainable design can refer to practical sustainability, environmental sustainability or a combination of the two. An example of practical sustainability can be observed in the DS106 community, which started out life as a digital storytelling class in the computer science programme at the University of Mary Washington (UMW) and was reimagined in 2010 as an open course by Jim Groom, Martha Burtis and colleagues (e.g. Groom & Burtis, 2010; Owens, 2011). The class evolved into a vibrant online learning community known simply as DS106. Participants outside of UMW created a DS106 radio station, which in turn inspired an internet TV station, all through the creative application of trailing-edge technologies. Using a variety of mediums, the community would set its own assignments, which were catalogued by the course team, becoming open educational resources for other educators to utilise in their own teaching practice. DS106 has become a self-sustaining community that continues to this day.

An example of environmental sustainability can be observed within the ACES international research project activities. Educators in Vietnam designed a multifunctional educational Green Playground space using recycled and reclaimed materials, which acts as an extension of the classroom environment, providing a safe recreational space for students that acts as a continuously evolving canvas for teaching students about sustainability and the natural world (e.g. Hoang et al., 2023). The repurposing of materials to build the playground helps prevent waste products that would otherwise end up in landfill, negating the need to purchase new materials and raising awareness of sustainability issues with participating students. The success of the Green Playground project has led to an expansion of the playground area, and ACES partners in Malaysia are working

TABLE 2 Leverage available resources: Proposed aspects, characteristics and considerations; linked to their respective source materials.

Aspects & characteristics	Considerations	Source material
Resourceful • Obtainable • Reusable • Reclaimed • Flex your assets • Donated • Recovered • Repurpose • Recondition • Remix • Improvise • Re-engineer • Recycle • Upcycle • Hack	• Leverage available resources that can be sourced from your local environment and wider community • Recycle, upcycle and combine materials and trailing-edge technologies in new and inventive ways, extracting untapped value and extending their lifespan • Inspire your participant by promoting a culture of resourcefulness	• ACES Malaysia: PlayLab Bus (Tan et al., 2023) • Doughnut Economics (Raworth, 2012, 2017) • Fab Lab (Fleischmann et al., 2016; The Fab Foundation, 2024) • Frugal Innovation (Radjou & Prabhu, 2015) • Frugal Science: Repurposing Existing Resources (Koopman & Gopal, 2017) • GameChangers (Arnab et al., 2017; GameChangers, 2024) • Jugaad Innovation (Prabhu & Jain, 2015; Radjou et al., 2012) • Kotoba Miners (York, 2014) • The Circular Economy (Stahel, 1982, 2016) • Toys from Trash (Gupta, 2013) • Trailing-edge Technologies (Groom, 2013; Udell, 2013)
Practical • Easy to maintain • Platform agnostic • Cost-effective • Fit for purpose • Feasible • User-friendly • Achievable • Manageable • Convenient • Time saving • Accessibility	• Consider the practically of your design • Consider the technologies and materials required • Consider the physical and virtual spaces you inhabit • Consider the intellectual and physical accessibility • Consider the financial and human resource costs of delivery	• CC Licencing (Creative Commons, 2023) • CreativeCulture (Arnab et al., 2019; *CreativeCulture*, 2019) • Doughnut Economics (Raworth, 2012, 2017) • Fab Lab (Fleischmann et al., 2016; The Fab Foundation, 2024) • Frugal Science: Foldscopes (Jackson et al., 2020) • GameChangers (Arnab et al., 2017; GameChangers, 2024) • Kotoba Miners (York, 2014) • Toys from Trash (Gupta, 2013) • Trailing-edge Technologies (Groom, 2013; Udell, 2013)
Resilient • Flexible • Robust • Scalable • Adaptable • Agile • Reconfigurable • Long lasting • Durable • Interchangeable	• Equip your designs with the flexibility to adapt gracefully to unforeseen circumstances • Avoid using custom materials that are impractical to source or reproduce • Try to utilise resources that are commonplace and interchangeable to make your design more accessible • Create a modular design that allows you to substitute component parts in response to changing needs and circumstances	• ACES (ACES, 2024) • CreativeCulture (Arnab et al., 2019; *CreativeCulture*, 2019) • Frugal Science: Flatbed Scanners for Imaging (Koopman & Gopal, 2017) • Jugaad Innovation (Prabhu & Jain, 2015; Radjou et al., 2012) • Kotoba Miners (York, 2014) • The Circular Economy (Stahel, 1982, 2016) • Toys from Trash (Gupta, 2013) • Trailing-edge Technologies (Groom, 2013; Udell, 2013) • UK Government Design Principles (GOV.UK, 2019) • UN: Sustainable Development Goals (United Nations, 2019)

with Vietnamese educators and students to co-create a similar space in a coastal village in rural Borneo.

An example of *iteration* can be observed in the incremental development of Kotoba Miners (e.g. York, 2014); a virtual language learning experience built by James York using Minecraft that has been built iteratively over a period of 10 years. Initially designed as an open world game environment for teaching English to Japanese students, a second iteration of Kotoba Miners was developed to teach Japanese to English students in response to a change in the user demographic. More English-speaking participants began joining the Minecraft server, and thus, the learning content changed to serve an overwhelming majority of English-speaking participants. As the virtual learning environment grew in complexity, further iterations lead to the creation of distinct geographic areas in a bid to improve performance and useability. Over time, additional hardware upgrades were required in response to the increasing performance requirements of the game and its respective server. As new technologies came to market, the Kotoba Miners community adopted more suitable solutions, such as a shift to the Discord platform for audio communications. Over 10 years, the Kotoba Miners community has continued to evolve their virtual world through iteration and collaboration, building new environments, activities and rules in response to the community's needs. The Kotoba Miners project employed creative problem-solving in collaboration with its participants, demonstrating a frugal approach to development through crowd-sourced world building, leveraging existing materials and resources in innovative ways to deliver impactful learning and embracing sustainability by establishing a self-sustaining online learning community built around the Kotoba Miners world. This is a great example of education practice in a digital context, demonstrating the advantages of frugal approaches to learning design.

Please refer to Table 3 for a breakdown of each aspect, its respective characteristics and considerations and the key source materials that provide a rationale for their inclusion.

The aforementioned frugal aspects have been applied as part of a novel approach for mapping 21st century competencies and resilience development in learners (Arnab, Mahon, et al., 2021). The mapping approach was applied by educators in Malaysia, Vietnam, Indonesia and the United Kingdom as part of the ACES international research project, funded by the GCRF: Global Challenges Research Fund and UKRI: Economic and Social Resilience Council (ACES, 2024). During the education design phase, the ACES team mapped aspects of learning, playfulness and frugality within each learning activity to help identify and define the various forms of engagement, interaction and outcomes the educators wished to generate within each learning design. The aspects mapping framework provides a means for articulating the context and design of the proposed educational intervention programmes. Alternatively, the mapping exercise can also be used to analyse learning, playful and frugal design aspects within an existing programme. It is recommended that each of the proposed aspects listed above be considered when seeking to create or adapt new and existing educational practices to be more frugal in their design, development and application.

5 | EXAMPLE APPLICATION: THE PLAYLAB BUS PROJECT

As a demonstration of the aspects within an existing design, we can explore the PlayLab Bus project undertaken at UNIMAS as part of the ACES project. The aforementioned frugal aspects have been emphasised in italics for easy identification.

The PlayLab Bus project transformed a decommissioned shuttle bus into a mobile Playful-STEM lab, offering an innovative platform for hands-on STEM education, particularly in rural areas (see Figure 2). By incorporating sustainable technologies like solar power, battery storage and rainwater harvesting, the project exemplifies frugal innovation through the repurposing of existing resources and the application of sustainable practices in an educational setting. The project fosters collaborative and interdisciplinary learning, encouraging creativity, problem-solving and environmental

TABLE 3 Build at the speed of need: Proposed aspects, characteristics and considerations; linked to their respective source materials.

Aspects & characteristics	Considerations	Source material
Minimal • Simple • Minimalist • Essential • Purposeful • At the speed of need • Function *over* form • Minimum viable pedagogy • K.I.S.S • Intuitive	• Be economical with the resources that constitute your design • Look to reduce administration, streamline processes and minimise costs • The simpler your design, the easier it will be to build, deliver and manage • Free up valuable resources that can be used to better serve your learners	• Academic entrepreneurial engagement for frugal innovation in HE institutions: a systematic literature review (Toyin Ojo et al., 2022) • Essentialism (McKeown, 2014) • GameChangers (Arnab et al., 2017; GameChangers, 2024) • Jugaad Innovation (Prabhu & Jain, 2015; Radjou et al., 2012) • Make Space (Doorley & Witthoft, 2011) • Toys from Trash (Gupta, 2013) • UK Government Design Principles (GOV.UK, 2019)
Sustainable • Economical • Affordable • Frugal • Easy to maintain • Supportable • Environmentally friendly • SDGs • Sustainable learning design	• Whether designing new or adapting existing practice, consider the wider impact of your design on the environment • Think about the first-order effects of your design decisions and how they might impact the local environment • Consider the second-order effects of your design from a global perspective	• ACES Vietnam: Green Playground (Hoang et al., 2023) • CreativeCulture (Arnab et al., 2019; *CreativeCulture*, 2019) • CU SPRINT/Micro SPRINT (Richards et al., 2017, 2019) • Doughnut Economics (Raworth, 2012, 2017) • Fab Lab (Fleischmann et al., 2016; The Fab Foundation, 2024) • Frugal Innovation (Radjou & Prabhu, 2015) • Jugaad Innovation (Prabhu & Jain, 2015; Radjou et al., 2012) • Make Time (Knapp & Zeratsky, 2018) • SPRINT (Knapp et al., 2016) • The Circular Economy (Stahel, 1982, 2016) • Tools for Systems Thinkers (Acaroglu, 2017) • UN: Sustainable Development Goals (United Nations, 2019)
Iterative • Evolving • Rapid prototyping • Trial and error • Real-time feedback • Iteration • Circular pedagogy • Test and refine • Responsive • Agile • Feedback Loop	• Do not overthink it • Start small and iterate often • Test the effectiveness of your design through rapid prototyping, giving you the flexibility to respond quickly and effectively to the needs of your audience • Design, resource, build and deliver quality education through a continuous cycle of improvement and refinement	• ACES Malaysia: STEMBucket (Minoi et al., 2023) • CU SPRINT/Micro SPRINT (Richards et al., 2017, 2019) • DS106 (Groom, 2013; Groom & Burtis, 2010) • Frugal Innovation (Radjou & Prabhu, 2015) • GameChangers (Arnab et al., 2017; GameChangers, 2024) • Kotoba Miners (York, 2014) • Make Space (Doorley & Witthoft, 2011) • SPRINT (Knapp et al., 2016) • The Circular Economy (Stahel, 1982, 2016) • Tools for Systems Thinkers (Acaroglu, 2017) • UK Government Design Principles (GOV.UK, 2019)

stewardship among students and educators alike. The PlayLab Bus is an outcome of the innovative CreativeCulture STEMBucket programme, which exemplifies the deployment of frugal education aspects in an academic setting.

The PlayLab Bus provides an avenue for young learners to experience STEM-related subjects in an interactive and engaging manner. However, during its redevelopment, the bus served a dual

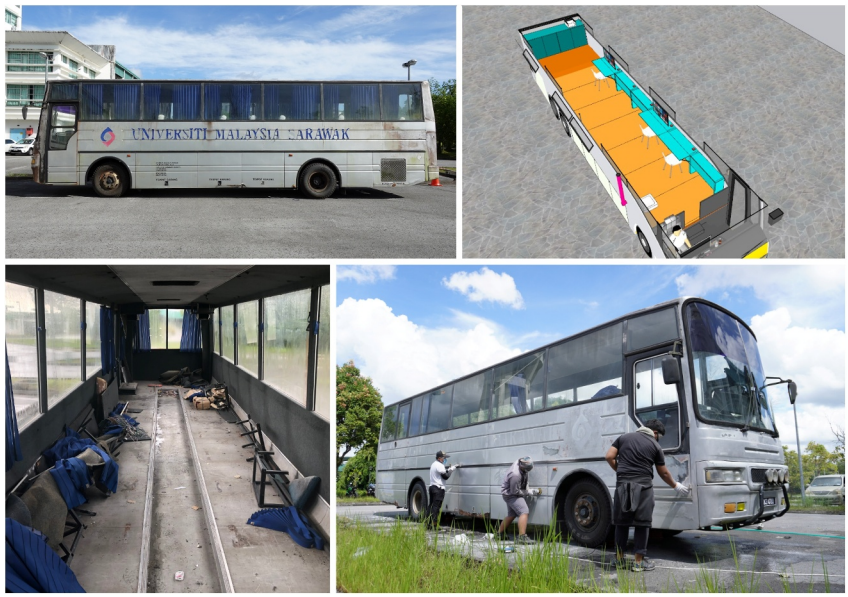

FIGURE 2 Clockwise from left: Delivery of donated bus, design concepts for the proposed interior design an initial exterior preparations. Work begins on the replacement of the flooring ahead of the internal refit.

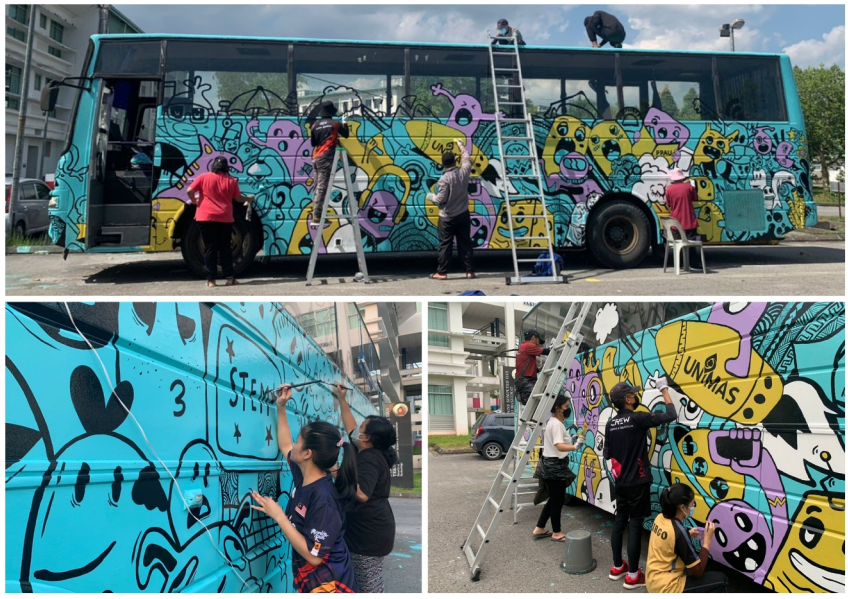

FIGURE 3 The CreativeCulture student team at various stages of the mural painting process.

purpose by also providing a platform for budding artistic talents within the university to express themselves by designing and painting a vibrant mural that adorned a majority of the vehicle (see Figure 3). In this endeavour, the students involved in the initiative displayed significant *creativity* and problem-solving skills, pushing the boundaries of their capabilities in a unique and challenging context.

The frugal education aspects deployed in the development of the PlayLab Bus encompassed several key strategies. Firstly, the *collaboration* with students as both designers and members of the production team ensured their active involvement in renovating the bus. This approach not only empowered the students but also fostered a sense of ownership and agency in delivering the project. *Resourcefulness* played a crucial role throughout the development process as students and staff collaborated to improvise solutions and embrace the recycling and up-cycling of materials and resources. This creative problem-solving approach not only minimised costs but also demonstrated the importance and potential of *sustainable* practice within educational initiatives.

Moreover, the design of the PlayLab Bus focused on building *practical* solutions to support the delivery of remote teaching and learning experiences. By creating a modular and flexible space, the bus became easily adaptable, allowing for efficient reconfiguration in response to changing needs and environments (see Figure 4). This flexibility enables the project team to address challenges and changing needs as they arise, ensuring that the design remains aligned with the evolving teaching requirements and environmental conditions. The *iterative* nature of the design process was another integral aspect of frugal education deployment. Through prototyping and continuous refinement, the design team gathered valuable feedback from both student collaborators and UNIMAS team members, enabling the design to evolve and improve over time.

In line with the proposed aspects of frugal education, the project aimed to achieve its objectives with *minimal* use of new materials and resources. By leveraging available resources and constraints, the team demonstrated their commitment to sustainable and economical practices, ultimately achieving the desired project outcomes within their budgetary constraints. When refitting the bus, functionality took precedence over aesthetics, emphasising the importance of fulfiling its intended purpose effectively. This prioritisation ensured that the limited UNIMAS resources available were directed towards enhancing the educational experience in the first instance. By offering the bus exterior as a blank canvas for creative expression, the student team was able to enhance the visual appearance of the bus in parallel to internal modifications, to allowing UINMAS staff to focus their time and expertise on refitting the internal teaching space to maximise the pedagogical impact of the initiative.

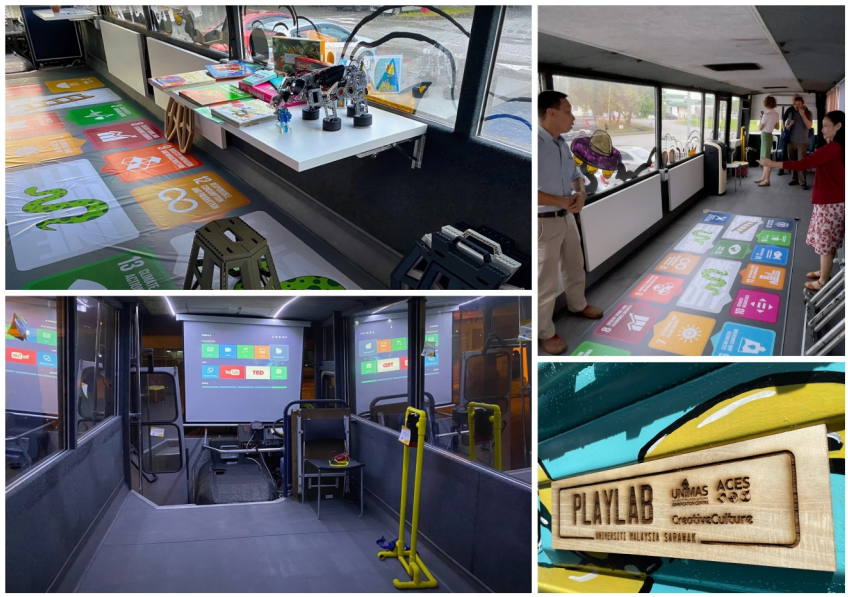

FIGURE 4 Example layout of the PlayLab Bus internal space, utilising hinged fold-away tables, concealed projection screens with mobile projectors, compact foldable chairs, privacy glass and energy efficient strip lighting.

Additionally, sustainability was consciously incorporated into the bus design through the implementation of rainwater capture, solar power generation, energy storage systems and the repurposing of disused bus seats as mobile indoor seating (see Figures 5 and 6). These features not only reduce the environmental footprint of the PlayLab Bus but also provide practical examples of sustainable technologies in action, further enriching the educational experience for participating students.

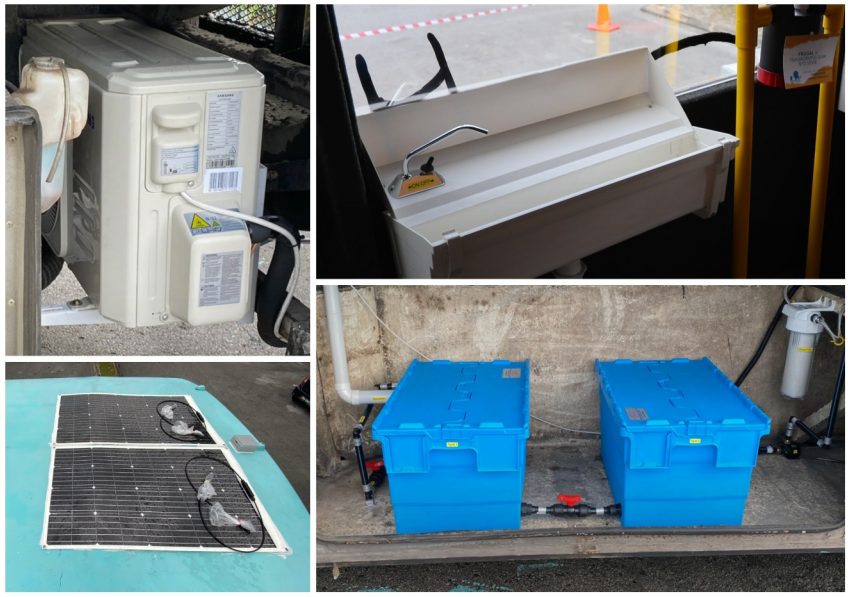

FIGURE 5 Clockwise from left: Roof-mounted modular solar panel system, retrofitted air-conditioning unit, indoor low-profile sink with a water dispenser and rainwater collection tanks with a water filtration system.

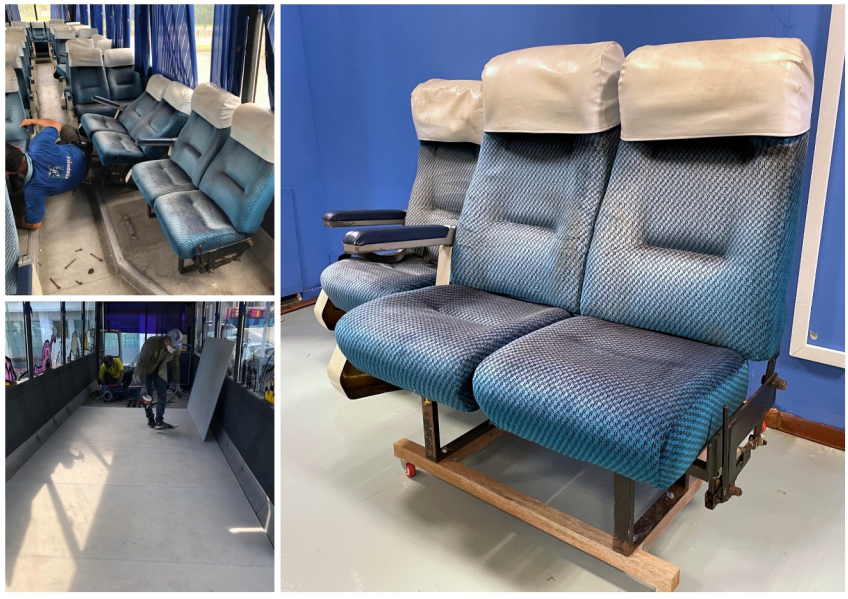

FIGURE 6 Before and after: The original bus seats were repurposed as moveable seating for use in the CreativeCulture lab. Seat pairs were augmented with wooden bases, complete with castors, to allow for easy movement within the space.

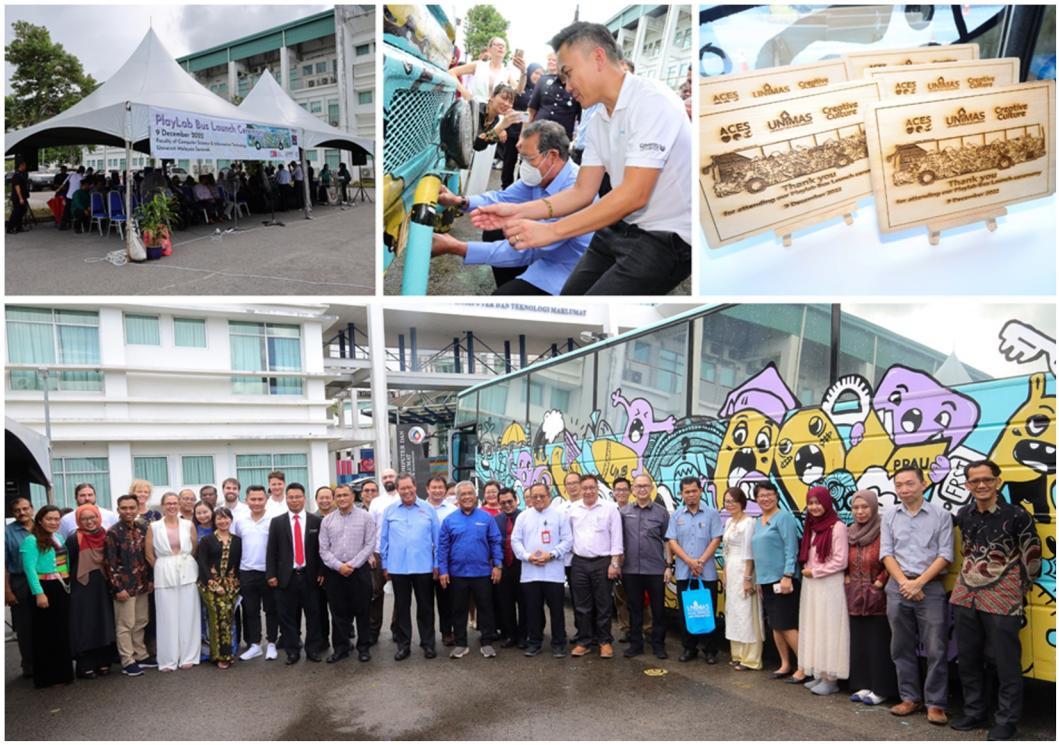

FIGURE 7 CreativeCulture PlayLab Bus launch ceremony, December 2022. Courtesy of Universiti Malaysia Sarawak, photography by Azlandy Mohammid Ali Tuah.

UNIMAS formally celebrated the launch of the Play Lab Bus in an official ceremony (see Figure 7), raising awareness of the sustainable and frugal practices demonstrated through successful reconditioning of the bus into a mobile frugal STEM learning environment. The PlayLab Bus, along with its parent STEMBucket programme, was instrumental in the ACES project winning the bronze QS-Wharton Reimagine Education Award for Sustainability Education in 2023 (Quacquarelli Symonds, 2023). Due to their high-profile success and recognition, the PlayLab Bus and STEM-Bucket programme have the potential to positively influence frugal and sustainable education practice and institutional policy at UNIMAS.

Based on an evaluation of the PlayLab Bus case study narrative published by the project team (Tan et al., 2023), Table 4 demonstrates how the frugal aspects have been applied within the project. Ultimately, through the thoughtful integration of playful and frugal education aspects, the PlayLab Bus emerged as a practical, adaptable and responsive mobile teaching space, capable of serving diverse communities at the speed of need thanks to its modular construction and resilient design philosophy. This initiative demonstrates the value of leveraging limited resources creatively and sustainably to provide enriching educational opportunities for young learners and foster skills development through a resilient learning design.

6 | DISCUSSION AND CONCLUSION

This paper argues that there is value in applying frugal innovation practices within an education context, specifically as part of the design process, and that the aspects proposed can serve as a creative aid towards achieving practical and sustainable education practice.

TABLE 4 Example applications of the frugal aspects identified within the PlayLab Bus project.

Frugal aspects	Example application
Creative	• Conversion of a dilapidated shuttle bus into a mobile STEM lab allows for hands-on STEM education • Use of the bus as a platform for artistic expression through mural-making by undergraduate artists • Creative problem-solving in response to uncharted territory when modifying the bus. Addressing technical challenges and emerging issues at the speed of need
Collaborative	• Co-creation process between students and lecturers in the mural-making assignment enhances learning through art • Engagement of multiple disciplines in creating practical innovations for self-sustainability in rural applications • The project acted as a research incubator, promoting collaboration between universities and target communities
Open	• Facilitates open access to digital services through a Digital Library and Education Portal for broader community engagement • The bus functions as a mobile open access resource that can be used by all members of a community within which it is located • Insights from the project informed the development of the ACES Charter (ACES, 2023), made freely available online as an open educational resource, licenced through Creative Commons • The project team is in the process of developing blueprints for the PlayLab design to be made available online to support other educators in the development of similar remote STEM-lab initiatives
Resourceful	• Implementation of a micro-scale rainwater harvesting system tailored for the PlayLab demonstrates efficient resource use • Adoption of a modular solar power system for self-sustained electricity showcases resourcefulness in energy management • Designing the PlayLab to be powered by solar panels for off-grid operation exemplifies the use of sustainable resources to maintain operation in off-grid locations • Improvised solutions to design problems using recycled and up-cycled materials and resources • Use of mobile projectors to enable the projection of mural design onto the bus during the evening for better visibility and cooler temperatures for more effective paint application and more comfortable working conditions
Practical	• Repurposing an existing shuttle bus allowed the project team to leveraging available materials, reducing the overall costs incurred to expand teaching and learning facilities • The creation of a modular and adaptable learning environment allows for the space to be easily reconfigured according to different educational needs and settings • An integrated computer server pre-loaded with educational resources, complete with Wi-Fi access point to enable local network connectivity • Solar panels and batteries for energy storage ensure that the PlayLab's electrical needs are met, powering appliances and educational tools without the need for electrical grid connectivity
Resilient	• The self-sustained electricity, water supply and air conditioning systems make the PlayLab Bus highly adaptable and resilient, capable of functioning autonomously in varied environments, ensuring educational activities can continue unhindered, regardless of external circumstances • Leveraging recycled and up-cycled materials for use within educational activities in response to local resource limitations • Collaborative problem-solving to address emerging challenges as a means of developing resilience through learning experiences for both students and staff

(Continues)

TABLE 4 (Continued)

Frugal aspects	Example application
Minimal	• Maximising impact with minimal resources was achieved through the reduction of new materials by repurposing existing assets • Emphasising the essence of frugality by achieving a multi-functional mobile lab with minimal expenditure, upkeep and operational complexity • Reducing the footprint of learning spaces through the creation of a multi-purpose space, capable of serving multiple educational disciplines
Sustainable	• The solar power generation system not only exemplifies the application of renewable energy in educational settings but also serves as a tangible lesson in sustainability for students • The integration of a rainwater harvesting system into the PlayLab design illustrates sustainable water management. By collecting and using rainwater, the project teaches valuable lessons on conservation and environmental stewardship • Upcycling of a dilapidated shuttle bus that would have been scrapped, thereby reducing waste, minimising resource consumption and maximising utility
Iterative	• The project's commitment to modular and iterative mobile learning space demonstrates a dynamic environment where educational practices can evolve • The PlayLab Bus serves as a prototype that will be continually refined over time in response to user feedback. This process ensures that the PlayLab remains an evolving and responsive learning environment

Abbreviation: STEM, Science, technology, engineering, and mathematics.

There is a strong relationship between the economical use of materials and resources and the development of sustainable practice within education. Experimentation within imposed constraints can be a catalyst for creativity when designing new education practice, specifically when including the target audience within the design process. By leveraging available materials and resources in creative ways, educators can extract greater value from existing technologies, spaces, budgets and teams, all while minimising waste materials as a means of addressing environmental sustainability. The open sourcing of education designs can aid in the proliferation of frugal and sustainable practice through knowledge sharing, combined with open licencing, to grant educators permission to adopt and adapt frugal approaches within their own learning environments.

This paper seeks to contribute to the existing knowledge and research into frugal innovation as it applies within the context of education, reframing the use of the term 'frugal' away from affordability and poor quality towards a more expansive understanding. Moreover, research outcomes will further enhance our understanding of sustainable innovation within educational environments. While non-exhaustive, the frugal education aspects proposed seek to establish a foundation on which to build, define and contextualise frugality within an education context. Future research seeks to further elaborate on these frugal aspects in the form of practical resources to support educators in the design of frugal education practice. One such resource proposed is a collection of exercises, taking the form of a handbook, to guide users through a series of creative prompts as a means of facilitating creative thinking and problem-solving within a chosen problem domain.

Another resource that has been developed and informed by the aspects defined in this paper is the 'Frugal Education Action Cards' deck (Masters, 2023). The resource takes the form of a physical card deck comprised of 27 frugal consideration cards. Each aspect is broken down into three considerations, organised under the three guiding principles, addressing design, resourcing and development. The cards have been implemented within case studies across Malaysia, Indonesia and Vietnam as part of the ACES international research project. These case studies represent an opportunity to empirically assess whether the application of frugal aspects can affect positive change within an educational context, under a variety of different scenarios, through their application within innovative education design and practice.

As for non-educational applications, there may be scope for frugal education aspects to impact wider society due to the fungible nature of the concept. After all, frugal innovation was born out of the hacker mindset and can be applied to almost any situation. It may be envisaged that these concepts can be introduced to students in a way that enables them to see the potential benefits of frugal education practice outside of an education design context. This may provide opportunities for further research into broader applications of frugal education aspects, looking at how students themselves might apply them towards addressing wider societal challenges through the perspectives of practicality and sustainability.

The frugal education aspects described in this paper are being adapted and adopted within various educational activities that include learning design, curriculum development, space design, teacher training, resource development and practice-based research through implementation within the ACES project in Malaysia, Indonesia and Vietnam. Future research will empirically evaluate the effectiveness of the frugal education aspects within a variety of different contexts and educational environments.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ETHICS STATEMENT

Research ethics approval for the ACES project was obtained by the ethics committee of Coventry University (reference number: P109635).

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