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DISCRETE EVENT SIMULATION FOR SUSTAINABLE HOSPITAL PHARMACY: THE CASE OF ASEPTIC SERVICE UNIT

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ABSTRACT

Within hospital pharmacies, aseptic units preparing high-risk injectable medicines face environmental and economic challenges due to resource-intensive processes and emissions. Variability in patient dosage requirements leads to inefficient drug vial usage, resulting in waste generation, carbon emissions generation from waste, and increased costs. Batching could be used to reduce resource consumption and reduce waste associated with single-dose preparation. This study develops a discrete event simulation, as a tool for strategy evaluation and experimentation, to assess the impact of batching on productivity and sustainability. The model captures key process dynamics, including prescriptions arrivals, production processes, and resource consumed. By experimenting with time-sensitive and size-based batching, the study evaluates their effects on the reduction of medical and nonmedical waste, thereby contributing to cost savings, reduction of carbon emissions, and productivity by enhancing workflow efficiency. This study offers insights for hospital pharmacies to evaluate batching strategies effectiveness for reducing waste and promoting sustainability.

1 INTRODUCTION

Greenhouse gas (GHG) emissions associated with healthcare are a significant driver of climate change; originating from various points across the healthcare system, including medical supplies, services and patient transportation (Rizan et al. 2021; Syed et al. 2022). As the effects of carbon emissions attributed to the healthcare sector are better understood, healthcare organizations are shifting toward a new paradigm in which their environmental impact are subject to increased scrutiny (van Daalen et al. 2022). In the UK, the NHS (National Health Service) accounts for 4% of the country's total carbon footprint while simultaneously facing challenges from environmental stressors that exacerbate health problems (NHS 2020). Supply chain activities within the UK healthcare system contribute to 62% of the NHS carbon footprint, with medicines and chemicals being major contributors (NHS 2022). According to the report "Delivering a 'Net Zero' National Health Service" (NHS 2022), carbon footprint from NHS waste streams and its medicine supply chain is increasingly recognized as both a financial and environmental burden, accounting for 5% and 25% of its total footprint, respectively.

Hospital pharmacies play a crucial role in medicine supply and management and can contribute to the NHS's net-zero targets. There is the ambition to reach an 80% reduction for their indirect (e.g., supply chain's) carbon emissions by the period 2036 to 2039 (NHS 2022). Within hospitals, aseptic service units (ASUs) are critical components of pharmacy supply chains, responsible for the preparation of high-risk injectable medications, such as chemotherapy drugs, parenteral nutrition, and monoclonal antibodies (Beaney 2006). However, ASUs are also highly resource-intensive, requiring strict sanitization procedures, and precise medication handling (Sánchez et al. 2023). The sustainability challenge in ASUs is further driven by high levels of waste including incomplete use of drug vials, waste from single-use personal protective equipment (PPE), and nonmedical consumables such as syringes (Rizan et al. 2021). A significant portion of waste results from production inefficiencies, limited drug stability, and patient-

specific dosing requirements, leading to unnecessary pharmaceutical disposal (Fasola et al. 2014; Kieran et al. 2024). Additionally, aseptic drug preparation involves variability in resource utilization, contributing to staff workload imbalances, hence social aspects of sustainability. Addressing these inefficiencies is essential to aligning ASU operations with sustainability objectives, including waste reduction, improved resource utilization, and cost savings.

Figure 1 illustrates how operational strategies can improve efficiency and sustainability performance within ASUs. Moving from right to left, to enhance sustainability key performance indicators (KPIs) - such as reduced carbon footprint through incineration of medical waste - one strategy for ASUs could be to first minimize waste generation. Minimizing waste requires reducing the consumption of inputs (e.g., drug vials, PPEs), as using fewer inputs to deliver the same number of doses arguably reduces some waste streams. Achieving lower input consumption, in turn, may depend on improving ASU efficiency. Efficiency can be improved through various strategies, including batching, automation, and centralized operations (DHSC 2020). The current study focuses on **same-day batching**, which consolidates the preparation of identical prescriptions to optimize input use and reduce waste. Two other strategies - automation and centralization - are presented as future opportunities. Batching derives the maximum use of inputs in the ASU processes by consolidating prescriptions in a hospital pharmacy and preparing them all at once, thereby enhancing operational flow. This reduces consumption of resources such as vials, PPEs and staff time, thereby decreasing the amount of waste generated in the unit and contributing to better sustainability performance.

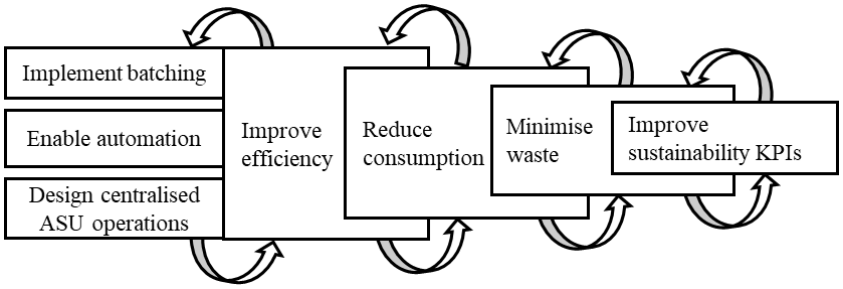


Figure 1: An overview of study's conceptual framework.

To support sustainability, hospital pharmacies require evidence-based approaches for enhancing efficiency while reducing their carbon footprint. One method is simulation-based modelling, which enables hospitals to understand the amount of waste generated in the unit, evaluate its impact on efficiency and sustainability performance, and experiment with waste reduction strategies in a risk-free environment before real-world implementation. This study employs discrete event simulation (DES) to evaluate batching strategies, introducing a novel approach by integrating environmental, social, and economic factors (the triple bottom line perspective) into batching decisions. The objective is to improve resource utilization, minimize waste and carbon emissions, and ultimately promote more sustainable practices in ASUs.

2 BACKGROUND

In the healthcare literature, numerous studies have been conducted to optimize operational efficiency, often focusing on cost reduction and service level improvement. However, sustainability considerations remain relatively underexplored. For example, Furushima et al. (2018) employed simulation to assess the impact of single-dose packaging on patient waiting times in hospital pharmacies, while Rupnik et al. (2019) developed a model to analyze the performance characteristics of a central sterilization of surgical instrument aiming to enhance material availability and reduce costs in the hospital sterilization process. Although both studies provide valuable insights into operational efficiency, they overlook sustainability dimensions, such as waste reduction and carbon footprint minimization. A study by Dewi et al. (2022) showcases attempts to capture sustainability perspective using a system dynamics model of a dental care to predict waste generated in the care setting. This study *(ibid.)* acknowledged the environmental implications of medical waste; it primarily adopted a high-level perspective by assessing the overall impact of dental services on waste

generation and associated environmental costs. However, it fell short of proposing operational strategies to actively minimize waste or optimize resource utilization.

DES mimics healthcare workflows as a series of discrete events, allowing researchers to test different policies under realistic but controlled conditions (Robinson 2008). The application of DES is widely recognized in various healthcare contexts (Philip et al. 2023; Wang and Demeulemeester 2023; Yousefi et al. 2020), including capacity planning for orthopaedic surgery (Harper et al. 2023), improving service efficiency in health centre operations (Shoaib and Ramamohan 2022), and hospital inventory management and replenishment (Gebicki et al. 2014; Jebbor et al. 2023).In the context of ASUs, DES studies focused mostly on outpatient flow for the administration of aseptically prepared medications and scheduling. Richardson and Cohn (2018) developed a DES model to predict the effectiveness of various make-ahead chemotherapy drug policies on patient waiting times and staff utilization. While their study estimated waste from pre-mixed drugs, they only accounted for medical waste and did not concern consumables used for those medications or broader sustainability aspects within ASU operations. Alzouman (2017) proposed a DES model to test strategies for expanding the production capacity in an ASU; further, to investigate the significance of changing staff shifts to address shortages and improve operational efficiency. However, it did not address sustainability concerns such as waste reduction or carbon emission. Chiu (2010) assessed the effect of predetermined intravenous batching schedule for intravenous waste. While the waste was assessed in terms of dose, volume, and cost, the focus was on discontinued returned medications; operational inefficiencies and waste associated with the aseptic processes were out of the study's scope.

Given the high levels of waste within ASUs associated with medicines, and high consumption of PPE and nonmedical consumables, integrating sustainability principles into DES modelling presents an opportunity to extend the literature, incorporating traditional efficiency-driven measures with sustainability triple-bottom line (economic, environmental, and social) metrics, and evaluate sustainable practices through computational modelling. Towards this, the study incorporates waste reduction strategies, including batching, into a DES model for hospital ASUs. Reduction of waste is expected to not only reduce the resource consumption (*contributing to cost saving and economic sustainability*) but also to contribute to reductions in carbon footprint (*contributing to environmental sustainability*). Batching is likely to positively affect resource utilization, leading to a reduction in operational pressure on ASU staff through reducing some repetitive production procedures, such as sanitization process for each aseptic session. This, in turn, potentially allows ASU staff to allocate more time to patient care (*contributing to social sustainability*). Moreover, service level is one of the factors affecting patient satisfaction (*contributing to social sustainability*). Thus, understanding the impact of waste reduction strategies on the service level would be necessary as patient satisfaction is one of the important factors of social sustainability (Khan et al. 2018).

3 MATERIALS AND METHODS

The conceptual modelling was developed through a comprehensive understanding of the problem, informed by stakeholder engagement. This process incorporated insights from informal semi-structured interviews with hospital pharmacy experts, and a waste audit conducted within the ASU in a separate study (Harrison 2024). These inputs provided practical context for identifying inefficiencies and sustainability challenges within ASU operations.

3.1 Overview of the Model

The ASU case study is based on a hospital in the UK. The processes are modelled through five main steps, as illustrated in Figure 2, across three primary room types: the *central room*, *support room* and *clean room*. It facilitates multiple production processes, with products moving through different stages. The start and end point for the processes within the ASU is in the *central room*, where prescriptions arrive and worksheets (containing prescription details and batch sizes, if batching required) are processed. Worksheets are then sent to the support room, where operators prepare trays with required inputs (e.g., vials, syringes, needles),

perform checks, and clean items before passing them to the clean room for production. Finished products return to the support room for labelling, and finally to the central room for pharmacist release.

Next, we discuss the generation of waste in the three rooms. Waste is generated primarily in processes ② to ⑤, as illustrated in Figure 2. While worksheet preparation ① may involve minor stationary waste (e.g., double printing), it lies outside this study's scope. In the support room, PPE, cleaning agents, and packaging generate "offensive waste", through material preparation and assembly process ② (though waste associated with packaging and cleaning agents is out of the study's scope). In the *clean room,* "cytotoxic waste" arises from used syringes or other nonmedical consumables required for the production process ③, alongside further "offensive waste" due to PPE usage by staff (Figure 2). Returning to the support room for labelling ④, another round of PPE is discarded. At the final release stage ⑤, partly used vials are disposed of as "medicinal waste". Batching strategies can mitigate waste by consolidating similar prescriptions, reducing input use (PPE, consumables, and vials) across processes ②–④.

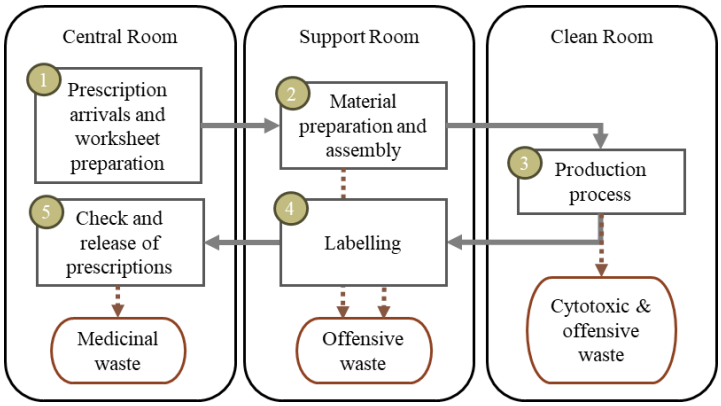


Figure 2: Overview of the ASU processes.

The boundaries of the model involve processes and waste associated with aseptic processes from the arrival of prescriptions at the ASU until the release of the aseptically prepared medicine for administration. Thus, discontinued prescriptions after release or waste due to administration errors are not considered. The model objective has been defined as to evaluate some streams of waste generated in the ASU and investigate waste reduction strategies and their impact on sustainability (including cost of consumed inputs for economic, carbon emission for environmental, and service level for social dimensions) performance as well as efficiency focused on resource utilization (both staff and inputs).

The model examines the impact of batching strategies on the reduction of waste streams in the ASU, including the waste from partially used vials (medicinal waste), the amount of PPE waste (offensive waste) and nonmedical consumables (cytotoxic waste). This is expected to improve efficiency through the reduction of waste and resource consumption, contributing to sustainability performance in ASUs.

3.2 Simulation Model

The current model is a proof-of-concept implemented using the DES software Simul8 on a Corei7 laptop, RAM 32 GB, and 64-bit operating system. It models the flow of prescriptions from the arrival of prescriptions to the completion of production. The output files and the Simul8 model are available upon request to the corresponding author. Figure 3 presents the flowchart of the simulation model. The flowchart is structured based on processes within the ASU rooms (refer to Figure 2 in section 3.1). This includes the arrival of prescriptions, batching decisions, and the release of medicines in the *central room*, assembly and labelling processes in the *support room*, and the production process in the *clean room*.

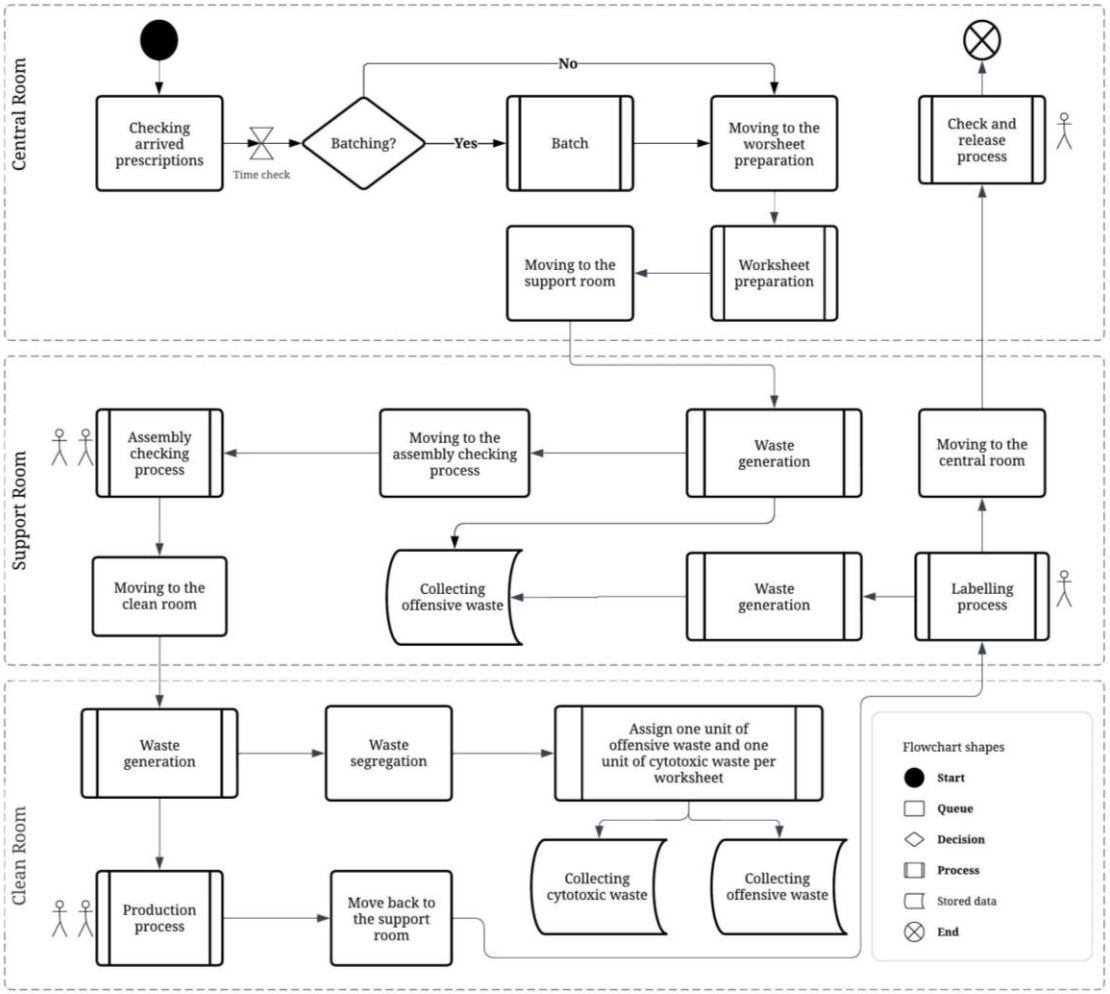


Figure 3: Flowchart of the ASU processes that illustrate the logic of the simulation model.

Prescriptions arrive at the entry point with an exponential distribution (mean=30 min). The prescriptions carry attributes including required dosage for each prescription, prescription number, and release time (for the prescription to be administered). For each prescription, the required dosage has been generated following a rounded uniform distribution.

Table 1 presents the input parameters used for the prescription's arrival. In the base model, as illustrated in Figure 3, the queue for arrived prescriptions is timely checked (every hour) and pushes the prescriptions to be processed without any restrictions (thus, in the base model there are limited batching; however, no restrictions are applied in terms of time or size for batching process). This means that even if there is only one prescription, it is pushed to the worksheet preparation process.

Table 1: Model components; distributions for arrivals and attributes.

Parameters	**Distribution**	**Parameters**
Prescription arrivals	Exponential	Mean = 30 minutes
Prescription number	-	Unique
Prescription dose	Rounded Uniform	Between 28 – 96 (mg)
Prescription release time	Rounded Uniform	Between 60 – 360 (minutes from entry time)

As per Figure 3, the prepared worksheet is sent to the support room for assembly checking process where for every worksheet, one pack of PPE is consumed by staff. It is assumed that each PPE pack contains a set of single-use gloves, single-use gown, cup fit FFP respirator and a surgical mask (Ernstmeyer & Christman, 2023). The model components, their descriptions and the simulation rule associated with each of them are shown in Table 2. For calculating medicinal waste, for each worksheet the total vials and dosage required (either 50 mg or 100 mg) are calculated, and the wastage of remaining vials for each worksheet are stored in an internal spreadsheet. The selection of vial size for each batch in the model was determined based on batch size and the total required dosage, with the objective of minimizing waste that might occur in individual prescription production. Specifically, the total required dosage was calculated for each batch, and the vial size that resulted in the least amount of leftover medicine was selected. For example, consider a worksheet containing three prescriptions (batch size = 3) with dosages of 35 mg, 65 mg, and 80 mg. The total dosage required for the worksheet is 180 mg. To determine the vial size, the model divides the total dosage by the larger vial size (100 mg), using the modulus function: 180/100 = 1.8. This result is rounded to the nearest whole number (100 or 50), giving 2 vials of 100 mg each. Thus, the total available dosage, based on available vial sizes, is 200 mg, and the waste generated is 200 − 180 = 20 mg. If the remainder had been less than 50 mg, a 50 mg vial would have been considered instead, to further minimize waste.

Table 2: Model components: Activities, resources, and parameters.

ASU processes	Description of activities and the simulation rules	Parameters	
Worksheet preparations	Collecting arrivals and pushing them into support room based on Simul8 *time check logic*. **Resource:** No operator required	*Process time:* dummy, fixed (0) [checking the queue based on time check logic]	
Material preparation and assembly checking	Collecting batches and generating one set of PPE waste per batch. **Resource:** Two operators required at the time of the process, **Priority:** FIFO	*Process time:* Triangular distribution (4, 6, 10) for small batches (equal or less than 5 prescriptions per worksheet)	*Process time:* Triangular distribution (12, 15, 18) for large batches (more than 5 prescriptions per worksheet)
Production	Collecting batches from support room and producing the medicine based on required dosage. **Resource:** Two operators required at the time of the process, **Priority:** FIFO		
Labelling	Collecting batches from the clean room and labelling the prescriptions as per the worksheet **Resource:** One operator required at the time of the process, **Priority:** FIFO	*Collection number**: based on batch size	*Collection number:* based on batch size
Check and release	Collecting batches from the support room and checking the produced medicines as per worksheet and medicines **Resource:** One operator required at the time of the process, **Priority:** FIFO	*Process time: fixed (5) minutes per worksheet*	*Collection number:* batch size
Waste generation	**Collect and assemble:** Collecting work items (prescriptions) and assembling them to generate one wasted input (PPE or syringe) per worksheet.	Dummy activity, fixed (0) *Collection number:* based on batch size	
Waste segregation	**Batching out function**: One PPE pack and one nonmedical consumable for each batches regardless of batch size.	Dummy activity, fixed (0) *Batching*** = Fixed (2)	

* Collect is a routing discipline in Simul8, and the collection number defines how many work items (prescriptions) are being collected from the associated queue; ** Batching feature in Simul8 is the term given for splitting up a work item into more than one work item. We used this feature to generate waste in the processes where identified waste creation points in the ASU.

3.3 Data

While specific hospital data is not used in the current model, the model parameters are informed by staff working in the ASU, literature on aseptic compounding units such as Smith (2015), Batson et al. (2020), and Baan et al. (2022), NHS sustainability documents available for public access (DHSC 2020; NHS 2023), and general standards for aseptic drug preparation based on *Good Manufacturing Practice* (GMP 2008). The waste streams have been estimated based on standard procedures for producing a single dose in the ASU and by Harrison (2024). In addition to parameters in Tables 1 and 2, two vial sizes were considered for the medicine: *100 mg* and *50 mg*. Since inventory management falls outside the scope of the study, it is assumed that all necessary materials—including vials, PPE, and nonmedical consumables—are always available. Additionally, staff availability is considered constant without considering shift-based variation.

To assess sustainability, for economic aspects representative costs of vial sizes were incorporated into the analysis, along with the prices of PPE and nonmedical consumables (Table 3). For environmental aspects, carbon footprint has been obtained and calculated, as presented in Table 3. To assess social sustainability, we focused on service level for patients' aspect, and resource utilization for employees' aspect. The service level has been calculated as the percentage of produced medicine in the exit point of the simulated model divided by entered prescriptions. For resource utilization, we relied on the percentages of a resource's availability that has been used up by the processes in the *Resource* result of Simul8.

Table 3: Input parameters for economic and environmental KPIs.

Type	Parameters	Sources
Economic		
• Price of medicine	£11 for 50 mg vials; £20 for 100 mg vials	British National Formulary (BNF)*
• Price of one pack of PPE	£2.1	
• Price of nonmedical consumable (e.g. syringe)	£1.8	
Environmental		
• GHG emission factor	Pharmaceutical = 0.581 kgCO2e/£**; Nonmedical consumables = 0.672 kgCO2e/£; Single glove: 0.026 kgCO2e/item; Cup fit respirator: 0.125 kgCO2e/item; Type IIR surgical mask: 0.02 kgCO2e/item; Single use gown: 0.905 kgCO2e/item	(Rizan et al. 2021a; Rizan et al. 2021b; GOV 2021)
• GHG emission for incineration	High-temperature incineration (for medicinal waste and medicinal contaminated sharps) = 1074 kgCO2e/tonne; Low-temperature incineration (for offensive (e.g. PPE) waste) = 249 kgCO2e/tonne	

* https://bnf.nice.org.uk/

** Kilograms of carbon dioxide equivalent per British pound

Scenarios: The model uses a time check logic that examines the queue based on time intervals (every hour for base scenario **(S0)** and every two hours for scenarios 1 and 2) and processes prescriptions based on the following strategies:

1. *Time-sensitive batching:* Prescriptions are batched based on their release time label. This means that on the time check logic, the queue for arrived prescriptions (refer to Figure 3) is checked and prescriptions that their release time have reached are pushed to be batched and processed (Scenario 1; S1).

2. *Size-based batching:* Prescriptions are batched based on a determined number of prescriptions. This means that when a defined number of prescriptions are available in the queue for arrived prescriptions, the prescriptions are pushed to be batched and processed (Scenario 2; S2).

3.4 Validation and Verification

The conceptual model was validated through a step-by-step review, including problem understanding, objective formulation, and the identification of relevant processes and components to be included in the model. The simulation model was then validated through checking the logic of the base model, conducted in collaboration with both domain and academic experts. A walkthrough process for the base model involved examining key model elements (e.g., prescription arrivals, batching logic, vial allocation, waste generation) to ensure consistency and realism. To enhance credibility, the model's workflows were compared with ASU processes and relevant literature, including studies by Baan et al. (2022), Smith (2015), Alrashed et al. (2021) and Gilbar et al. (2022), ensuring alignment with real-world operations.

3.5 Experimentation and Model Output

The experiments are executed for one simulated month and model the ASU facility working five days a week (Monday to Friday, 8 am to 5 pm). We conducted 20 replications for each scenario to account for variability. The results are reported using the mean values and 95% confidence intervals to support the comparison of performance across different batching strategies. The model used comparative analysis between the key performance indicators, including economic (cost of consumed/ wasted resources), environmental (carbon footprint), and social sustainability (service level and resource utilization). For process efficiency, we reported on resource consumption and utilization (vials and staff utilization; Table 4), to report simulation outcomes. Resource utilization contributes to social sustainability by enabling aseptic staff to be more productive while assigning less time to medicine preparation and production processes. By reducing the time spent on preparing one prescription per batch and managing frequent batch setups, staff can redirect their time towards more patient-centred responsibilities and or training, thus expected to lessen the working pressure in aseptic services.

4 RESULTS AND DISCUSSION

The outcome of the simulation model for each of the scenarios including base scenario, time sensitive batching, and size-based batching has been presented in Table 4. The simulation results indicate that while the base scenario achieves the highest service level (99.45%) for social sustainability and process efficiency KPIs, it also generates significantly higher carbon footprint (1234 $kgCO_2e$) and total costs (£2092), with the equivalent cost of wasted medicine vials reaching average of £840 and the average cost of consumed PPEs and non-medical consumables at £974 and £278 respectively (refer to Table 4). The base scenario operates by checking the prescription queue every hour and batching prescriptions without restrictions. This approach may result in batching prescriptions whose release time are not imminent, often leading to the creation of a single prescription per worksheet (batch size = 1). Consequently, this increases the consumption of PPE and non-medical consumables, while also contributing to higher vial wastage.

The number of prescriptions (which are single doses of medicines) pooled together in a worksheet determines the batch size. Figure 4 presents a comparison of carbon footprints generated for all three scenarios. The results show that the base scenario (S0) produces significantly higher carbon emissions, over 33% more, compared to the alternative scenarios. This increase is largely attributed to the more frequent occurrence of single prescriptions per worksheet (batch size=1), as also illustrated in Figure 5. In the base scenario, the number of worksheets containing only one prescription is notably higher (n = 25, refer to Figure 5), leading to increased resource consumption, waste generation, and higher carbon footprint. By

Table 4 Comparing model outcomes; base model (S0) and two scenarios (S1, S2).

KPIs/ Scenarios	S0: Base model	S1: Time-sensitive batching	S2: Size-based batching
Economic sustainability and process efficiency			
Equivalent cost of wasted vials (£)	840 ± 37	555 ± 30	535 ± 5
Cost of consumed nonmedical consumables (£)	278 ± 3	154 ± 2	157 ± 1
Cost of consumed PPEs (£)	974 ± 12	540 ± 5	550 ± 5
Total cost (£)	2092±43	1249±33	1244±21
Total number of consumed 100mg vials	220 ± 8	212 ± 6	216 ± 7
Total number of consumed 50mg vials	70 ± 2	44 ± 3	44 ± 2
Environmental sustainability			
Carbon footprint for medicinal waste (kg CO_2e)	492 ± 21	325 ± 12	313± 12
Carbon footprint for wasted PPEs (kg CO_2e)	545 ± 7	302 ± 2	308 ± 2
Carbon footprint for wasted nonmedical consumables (kg CO_2e)	197 ± 2	109 ± 1	111 ± 1
Total carbon footprint (kg CO_2e)	1234±25	736±19	733±12
Social sustainability and process efficiency			
Service level %	99.45 ± 0.16	97.04 ± 0.35	98.89 ± 0.32
Resource utilisation in the support room %	34.86 ± 0.49	18.07 ± 0.24	18.42 ± 18
Resource utilisation in the clean room %	17.80 ± 0.23	10.72 ± 0.15	10.93 ± 0.11

implementing time-sensitive (S1) and size-based batching strategies (S2), the number of single prescriptions per worksheet is reduced, and more prescriptions are pooled together per worksheet, resulting in larger batch sizes (ranging from 2 to 12 prescriptions per worksheet). This approach minimizes input waste, lowers waste-related costs, resulting in total costs of £1249 and £1244, and reduces carbon footprint to 736 kgCO_2e and 733 kgCO_2e in S1 and S2, respectively (see Figure 4 and Table 4). These findings suggest that optimized batching policies contribute to both economic and environmental sustainability. The comparison of S1 and S2 suggests that their KPIs are comparable (refer to Figure 4). This indicates that both scenarios may offer similar sustainability benefits, though further differentiation might emerge when tested with real-world data that captures additional variability.

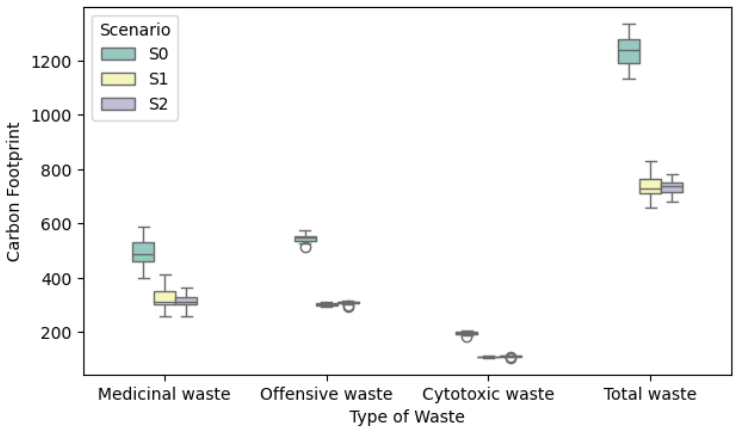
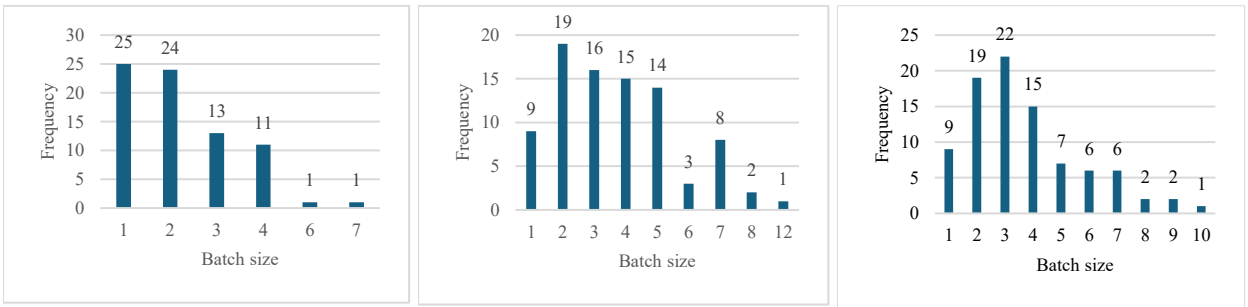


Figure 4 Comparing carbon footprint for offensive (PPE) and cytotoxic (medicinal waste and medicinal contaminated sharps) waste in the ASU (20 replications).

The service level for S1 is slightly lower than the other two scenarios, with an average service level of 97.04% (Table 4). The time-sensitive batching logic in Simul8 operates by checking every two hours whether a prescription's release time has been reached before allowing it to enter the aseptic processes. If

the release time has not yet arrived, the prescription is kept in the queue until the release time. This ensures that prescriptions are only processed when they are due to release, allowing time for other prescriptions to arrive and be potentially batched into the same worksheet, thereby reducing medicinal waste. A significant improved resource utilization is observed in the batching strategies (S1 and S2), more than 45% in the support room and more than 41% in the clean room, compared to the base scenario (S0), as shown in Table 4, showing improved efficiency which can potentially contribute to enhance social sustainability.

Our results align with findings from Smith (2015), who analyzed drug doses compounded over a two-year period in a general hospital and identified financial benefits from batching and vial sharing. However, they did not examine the environmental and social impacts of batching. Our study finds that, in addition to financial benefits, batching also reduces carbon footprint by minimizing medicine and consumable waste within the ASU. Moreover, the DES model has the potential to be used for different drugs with diverse profiles, including different arrival patterns, varying processing time, different prices, etc.



Base scenario (S0) *Scenario 1(S1)* *Scenario 2 (S2)*

Figure 5 Number of prescriptions in a worksheet (also referred to as batch size) and frequency (y-axis).

5 CONCLUSION AND FUTURE WORK

This study developed a DES model to evaluate the impact of sustainability-driven strategies on production efficiency and waste reduction in hospital ASUs. By incorporating key process dynamics such as prescription arrivals, production workflows, batching strategies, and waste generation, the model examines the trade-offs between cost savings, carbon footprint, and resource utilization (staff and input). The findings suggest that batching strategies (S1 and S2) can significantly reduce resource consumption, minimize waste streams including medicine vial waste, single-use waste, and waste of nonmedical consumables, and improve overall productivity. These results highlight the potential of DES as a decision-support tool for hospital pharmacies aiming to integrate sustainability considerations into their operational strategies.

It is important to note that these results serve as proof-of-concept for assessing the impact of batching on waste generation in the ASU. The findings will be more meaningful when applied to real-world datasets which is planned in the next phase of the study. Despite the study's contributions, there are some limitations which could be addressed in our future extension of the model. The carbon footprint calculated in this study only account for the disposal stage of the product life cycle and concerning only a subset of waste streams in the ASU (medicinal waste, PPEs and consumables). A life cycle assessment, including emissions from production and transportation as well as emission associated with inventory management of the medicines such as electricity usage for fridge, etc., is expected to provide a more comprehensive understanding of environmental impact. Furthermore, the current model simulates a single-product production process within the ASU. Future extension of the model is planned to extend the model to include multiple products with varying prescription arrival patterns to better evaluate the broader implications of batching strategies. Additionally, incorporating an overtime working element into the model could further enhance the understanding of workforce efficiency, resource utilization, and cost implications in managing aseptic unit operations more effectively. In the present study, the economic aspects only cover the cost of waste. Incorporating different costs including inventory holding, maintenance for aseptic equipment, staff salary,

and cost associated with supply of the material in the future model, the proposed model can be refined to better support realization of sustainability-related KPIs along with efficiency.

This study makes several contributions to the field of sustainable healthcare operations and medicine supply chains. First, it integrates sustainability considerations, such as waste reduction and carbon footprint minimization, into a DES model for aseptic processes, an area that has been underexplored in previous studies. Second, the study highlights the potential of batching strategies to enhance operational efficiency while reducing both medical and nonmedical waste, providing insights for decision-making in hospital pharmacies. Finally, the study presents a model for complex ASU workflows, which can be adapted for future research incorporating real-world data and extended sustainability metrics.

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