Building Integrated Agriculture Information Modelling (BIAIM): An integrated approach towards urban agriculture

Abstract
Urbanisation is transforming human societies in many ways. Besides bringing benefits to people in cities, it also has negative impacts such as food security. One way to meet the challenge is urban agriculture; however, traditional agricultural practices are not suitable within urban areas due to limited availability of land. Therefore, the alternative option is to grow crops inside or on top of buildings, e.g. building integrated agriculture (BIA). But, there is limited research and information available for designers and planners to design such buildings. The presented research project bridges the gap between agriculture and architecture by proposing a building integrated agriculture information modelling tool in integration with Building information modelling. The plugin tool has data on plants’ requirements and automatic response to environmental factors. Environmental factors include temperature, light, water, nutrients, air, humidity, spacing and support. In this paper, seasonal tomato is selected as a reference crop, and the impact of environment (temperature, light, water, nutrients and spacing) on its health is discussed and simulated for germination stage. The undertaken project contributes to the concept of BIA and BIM maturity level, which would help to design an optimum environment building for plants.

Keywords: Urban agriculture (UA); Building integrated agriculture (BIA); Building information modelling (BIM); Greenhouses; Environmental factors; Building integrated agriculture information modelling (BIAIM); Controlled environment agriculture (CEA); Plugin

1. Introduction
The rapid urbanisation around the world has numerous impacts on urban society [3-6], and one of the most significant impacts is food security [7-10]. As cities grow, agricultural land is converted into residential areas [11] reducing the available cultivable land. In addition, deforestation, desertification and salinization have also altered the natural landscape of the earth, and have further intensified the problem of agricultural production and food security [12]. In contrast, arable lands cannot match the increasing deterioration [13]; when most of the available land is already being used for agricultural practices [14] . Consequently, there is massive pressure on farmers to produce more food from shrinking land [15], and there is a need to sustain agricultural sustainability and profitability without compromising ecological assets [13]. Urban agriculture (UA) is re-raised as an alternative solution to meet these challenges [16], which means bringing agriculture to urban areas. At Present, more than 800 million people are practising UA across the world [17]. UA represents food production practices that are situated inside or surrounding an urban region using human and natural resources, services, and in-situ products to cultivate, process and distributes food products [18].
Historically, these practices have been used in many countries, while developed countries have also started taking interest due to increasing food security problems [19]. However, in urban regions, available land is limited therefore UA can be in two ways: open rooftop farming; or high-tech controlled environment agriculture (CEA) [20], which provides ultimate results by providing optimum conditions [21].

CEA has been adopted to cultivate off-season crops and producing high-quality crops [22]. Though, for controlled environment building integrated agriculture (BIA), there is limited literature available. The key issue is the structural design of such modern BIA design; where the information on the plant-environment relationship is not available on state-of-the-art building designing tools [23-25]. For such practices to be possible, experts from various disciplines, i.e. agriculture, agronomy, architecture, urban planning, engineering, economics and public health will have to come together and work collaboratively [26]. Such intelligent collaborative platforms are also known as Building information modelling (BIM). BIM is a methodology, comprised of processes to generate and manage the information of building or group of buildings [27]. BIM can also be defined as “modelling technology and associated set of procedures to produce, communicate and analyse models” [28]. BIM tools get people and information working together effectively and efficiently through defined processes and technology [29]. Most of the developed countries have been using these tools for improvement in productivity and cost-savings throughout all stages of architectural, engineering and construction (AEC) industry [30]. Therefore, BIM is ideal for designing and managing agricultural buildings as well; and in this research, the focus is on BIM tools and objects’ attributes that it contains.

BIM was introduced more than two decades earlier, which distinguished 3D information-rich model from 2D drawings [31]. Also, BIM-based tools are becoming more common in the industry and academia alike. According to National BIM Report, 54 % of the AEC industry using BIM at some stage of their project, while 86% are expected to be using it in a year time [32]. Among many, Autodesk Revit and Graphisoft’s ArchiCAD are leading BIM tools available [33]. These software tools not only have 3D object libraries, but also their attributes, and much useful information to help through the design, construction and maintenance phases. For example, Figure 1 shows a window object in Revit containing: physical parameters; and, analytical properties.
However, these tools do not provide intelligent plant libraries containing: plants’ attributes; environmental factors; or their relationship to the environment, which could assist designers and planners to understand the plant-environment (P-E) relationship and manage that information in a BIM environment. Figure 2 shows the properties of BIM plants in Revit: the only geometric component is height, which only reflects a fully mature plant; and the rest of properties are like any other building component, for example, appearance, model, manufacturer and cost.
Unlike Revit, ArchiCAD does have the option to manipulate more geometric properties: height and diameter; and plants from all four season can be selected depending on the real-time condition of the site. Although it has some more features than Revit, important environmental factors: light, temperature, spacing, etc. are not considered. Similarly, Vectorworks BIM has some additional parameters, yet not enough to support through BIA design process [34]. Although, there is vital intelligence in BIM tools, however, it still is evolving and in many ways at innovation stage [35]. There are many challenges and barriers involved that are hindering the development and adoption of BIM. 1) BIM competency identification [36], 2) BIM maturity level, 3) training costs and 4) investment in new technology without the justification of potential savings [37]. This research is partially dealing with the second and partially with the fourth challenge improving the limitations of BIM plant libraries, which are summarised as follows: immature existing information, lack of analytical information, plants integration issues, plant-environment relationship, real-time simulation and limited physical properties. Therefore, this research proposes a BIA and BIM-integrated platform, building integrated agriculture information modelling (BIAIM) to design and provide environmental conditions’ information for plants.

This research is a part of an ongoing doctoral research, and this paper only covers the partial development of the platform. The paper is organised as follows: Section 2 presents state of the art on UA, CEA and BIA and, BIM and its applications. Plugin development and, environmental factor and simulation analysis are discussed in Section 3. Section 4 comprises on the discussion
of findings from the literature, and this research by pointing out factors for improvement is provided. Finally, the paper concludes with Section 5.

2. State-of-the-art

2.1. Urban and Controlled Environment Agriculture

Urban grown food has significant health benefits, and a large-scale expansion can highlight the benefits of fresh fruits and vegetables [18]. Goldstein, Birkved [38] and Goldstein, Hauschild [39] have discussed considerable advantages of UA over traditional agriculture. Among other benefits, it can provide substantial job opportunities in low and middle-income countries [40]. In addition, Choguill (1995) [41] summarised three key drivers for the development of urban agriculture: ability, necessity and opportunity; while [42] stated urban growth, environmental impact and food insecurity. Besides, unused or abandoned land also engage dwellers in utilising it for agriculture [43]. Furthermore, it can also bring significant socio-environmental benefits without increasing urbanisation pressure if implemented in neglected buildings [44], and ultimate results can be achieved if buildings provide a controlled environment.

Controlled environment facilities, also known as greenhouses, have a variety of a simple structure used for germination to a more complex controlled environment, delivering suitable environmental conditions for plants throughout the year. Hydroponic methods, where water is used as a growth medium are often referred as the complex controlled environment and also termed as controlled environment agriculture (CEA) [45]. There has been quite significant research to improve traditional greenhouses’ performance; especially related to energy, which is the main concern for controlled environment. One of the prominent work has been done by Cuce, Harjunowibowo [46], who used complex engineered integrated energy and heating systems to enhance the performance of existing greenhouses. Their findings clearly showed that up to 80% of energy could be saved within 4-8 years, considering the climate and crop types. Although energy is a critical factor, it also relies on an effective mechanical, electrical and plumbing (MEP) system that provides all the resources to plants.

On MEP systems, Chauhan, Kumar [47] reviewed the work that has been done on greenhouse dryers and found that the performance of dryer under forced convection mode was found better for high moisture crops, during natural convection system for low humidity. Similarly, Esen and Yuksel [48] have designed and successfully tested a biogas, solar and ground heat pump. The system could provide optimum temperature for crops. While, to improve irrigation and heat system of the greenhouse, Hong and Hsieh [22] proposed integrated control strategy over time control, which could save up to 90% of both resources. Their research showed that maximum crop response depends on optimum environmental condition. Panwar, Kaushik [13], in their research, found that the maximum crop response depends on the optimum environmental factors that its growth. They reviewed the available literature on ventilation, cooling, heating, and thermal modelling structural analysis and experimental studies. They found that controlled environment conditions are better than open field condition for crops, e.g. increase yield, and early and higher germination rate. Lastly, they concluded their research by arguing that all year around cultivation is possible if controlled environment is provided,
which will lead renewable and sustainable practice, especially for developing countries. Though, for creating controlled environment, all systems should be integrated with the structure

To improve the structural design, Kumar, Jha [49] tested the effect of greenhouse design on floriculture crops. They used Gerbera as a case study crop and creates a suitable microclimate for crops. The results showed that side openings and angle of roof vent influenced the model significantly. Therefore, the design of the structure is a critical component in providing optimum environmental conditions. To support the idea of closed greenhouse, Vadiee and Martin [50] proposed a conceptual closed greenhouse model to save energy. Although, they concluded considerable savings in energy, the proposed concept is neither evaluated nor considers materials’ construction. In addition, plants and their environmental requirements are also not available for designers, who will select materials and design of the structure. Nevertheless, the study provided enough analysis to support the concept of building integrated greenhouse. It also incentivises that controlled greenhouses can be multi-storey and will be more economical and productive. Whereas, on a commercial level, high demand for energy can be met by using fuel cell technology along with other renewable technologies [51]. Perhaps greenhouses can be built more resilient using open control systems like Groener, Knopp [52] described in their research.

2.2. Building Integrated Agriculture (BIA)

Although there is limited literature available on BIA; however, the idea is not new, and there are many aeroponic and aquaponics building integrated farms exist [14, 53]. Most farms do not have specific agricultural structures and are built in abandoned buildings. For example, world’s largest building integrated greenhouse has grown over 250 types of green crops and selling more than 20 at commercial level [54], which is built in an abandoned building. BIA can benefit in designing truly sustainable cities by incorporation of a more detailed evaluation of the land, water and energy consumption during food production, delivery and disposal processes. Hydroponic systems are one of the most efficient forms of BIA [55]. Furthermore, if crops are grown vertically using hydroponic systems, the farm can generate 20 times more yield and only uses 8% of water compared to traditional practices [56]. Table 1 shows some of the existing hydroponic farms in the world.
<table>
<thead>
<tr>
<th>Location</th>
<th>Owner</th>
<th>Details</th>
<th>Location type</th>
<th>Crop Type</th>
<th>Area (m²)</th>
<th>Energy Source</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Korea</td>
<td>Rural development authority</td>
<td>Three stories tall experimental</td>
<td>Rural</td>
<td>Lettuce</td>
<td>450</td>
<td>Grow light</td>
<td>Alter [57]</td>
</tr>
<tr>
<td>Singapore</td>
<td>Sky Greens</td>
<td>Commercial four stories tall</td>
<td>Inside the city limits</td>
<td>Chinese Cabbage, Spinach, Lettuce, etc.</td>
<td>70 (expanding)</td>
<td>Sunlight</td>
<td><a href="http://www.skygreens.com">http://www.skygreens.com</a></td>
</tr>
<tr>
<td>Chicago</td>
<td>Farmed Here</td>
<td>Commercial</td>
<td>Inside the city limits</td>
<td>Baby green, Broccoli, and Kale</td>
<td>5574</td>
<td>Uses sunlight</td>
<td>Robarts [60]</td>
</tr>
</tbody>
</table>
Among several existing forms of BIA, Rooftop Greenhouse (RG) farming is the most popular since rooftops represent a significant unutilized urban area, and lightweight hydroponic greenhouses do not necessitate any major structural reinforcement of buildings. Several North American companies have already proven that substantial amounts of food can be produced year-round for urban dwellers on unutilized rooftops in dense urban settings where free and affordable land is exceptional [61]. Rooftop farms or gardens have been in practice for many years, and they are operating as the proof of concept. Currently, New York City (NYC) is at the forefront of BIA rooftop farms, for example, 40000 ft² Brooklyn Grange Farm and 6000 ft² Eagle Street Rooftop Farm, which have produced and a wide range of crops [45]. This approach can have a significant contribution to the environment, food security and economy if adopted at a greater variety.

Sabeh [62] mentioned benefits like low energy consumption, stormwater management, heat island reduction, carbon sequestration and building insulation. Specht and Sanyé-Mengual [63] and Specht, Siebert [64] reviewed existing literature on rooftop agriculture, which illustrates its benefits, limitations, potential and contribution to the community if right policies are put together. Nonetheless, each type of BIA has its advantages and constraints, for example, vertical hydroponic plants have limited height available, and higher crops cannot be suitable; and it has a higher yield, low water and nutrient requirement. In a case study, Pons, Nadal [65] found that BIA produced tomatoes are cheaper, having lower environmental impact and have sufficient cultivation temperature due to building’s thermal inertia. Although BIA has started getting attention recently, there are currently no adequate tools available to design a building that has intelligent plant libraries to assist through planning, design and management process. Nonetheless, smart tools like BIM has the potential to host such libraries.

2.3. Building Information Modelling (BIM)
BIM has been assumed and defined in many ways, and its versatility has caused discussion about its validity and applicability. It has been considered a methodology and set of processes to digitally represent and exchange the knowledge and information about construction projects, providing decision support throughout its lifecycle [66]. In addition, BIM can enhance not only the processes but also have the capability to facilitate alternative approaches [67]. BIM process and workflow is shown in Figure 3. The workflow shows how BIM methodology can assist throughout the project; from evaluation to maintenance. With a variety of systems, BIM is transforming the way projects are designed, engineered, deliver, manage and maintain [68]. In conjunction, it is a process that runs throughout the life of an asset. Bradley, Li [69] summarised BIM as a concept, process and methodology comprising on four key elements: collaboration, representation, process and lifecycle; all are interrelated to provide efficient and innovative project platform. While [70] has discussed BIM process throughout the lifecycle: design, construction and management.
BIM provides a platform to gather both graphical and non-graphical information of the building project, which focuses on the possibilities of utilisation of that information than what it contains. In addition, it comprises the tools and technologies to improve the collaboration in the construction industry, which enhances the productivity by improving planning, design, construction, maintenance and management [33], whereas 3D graphics and related information have broadened the knowledge of the user [72]. BIM tools can also help to effectively design, simulate and validate multidisciplinary (i.e. architectural, structural, electrical, mechanical, plumbing and ventilation) projects on a single platform [70, 71].

This versatility makes them ideal for designing a building integrated greenhouse that would need all these systems. In addition, it has intelligent objects [75], and customization of these tools can improve the design process efficiency, and minimises designers’ efforts on additional and recurring activities. BIM provides significant benefits to the facility designers and owners and users such as solar and energy analysis, better environment, water efficiency and owner’s satisfaction [74, 76]. Although, BIM is transforming AEC industry by providing precise, suitable and related information throughout the lifecycle of a building. Conversely, it has not been fully adopted, which can be divided into four levels: starting from level 0 to level 3 (CAD drawing to fully integrated) as shown in Figure 4.
The majority is still working on level 1 that is 2D-3D modelling; while others are on level 2, and getting significant benefits from it by utilising it as a tool for advanced visualisation and collaboration [79]. While the potential of BIM for facility management is yet to be exploited; however where adopted, the advantages are very significant [80]. Therefore, considering its significant potential, in this research, we stimulate the potential of BIM for BIA facilities.

Some Architects believe that it is sensible to bring farming where everybody lives [81]. The idea is that a building integrated greenhouse will be able to produce crops all over the year, providing safe, high-quality and fresh food. Within a greenhouse, environmental factors can be controlled to provide optimum growth condition. Environment factors include the following: temperature, water, light, nutrients, space, air, humidity and support [78-82]. First five factors are considered in this research, and are further explained in section 3.1. The concept of high-tech UA is still in its infancy to conclude its applications and socioeconomic success at a global level [14]. In contrast, this concept will reduce transportation expenses and CO2 emissions linked with delivering the food to distant locations [87]. In summary, to achieve the benefits of UA and BIA, BIM’s multidisciplinary platform can also be integrated to design and manage agricultural facilities, which will not only exploit BIM potential but also enhance its maturity.
3. Building Integrated Agriculture Information Modelling (BIAIM) Plug-in Development

The proposed framework has three main components: database development, which contains the information on environmental factors, plants attributes and Plant-Environment (P-E) relationship; BIAIM user interface development, which has three modules to visualise, analyse and manage data; and integration of BIAIM and BIM. The BIAIM development framework is shown in Figure 5.

Environmental factors need to be considered and analysed prior to the development of the database. While building components that will be affecting the plant growth are HVAC, Lights, Site, Space and growing media [88, 89] can be designed in BIM tools. All these components influence plant growth directly by influencing the environment, therefore, having an impact on plants’ growth. For BIAIM database, P-E relationship study provides an insight how various
plant species have different environmental requirements. In this study, the seasonal tomato is selected as a case study crop. Although, every crop has four stages, initial, development, middle and final. At this juncture, the initial (seedling germination stage) is selected as it’s the first stage of the process. Simulation and sensitivity analysis are conducted to analyse the environmental impact on germination. The data is stored in a SQL database, and for visualisation, Autodesk Revit (BIM) is selected as Revit also uses SQL database. Along with .NET framework, Revit API is used to develop the BIAIM plugin and its user interface, and link the databases.

3.1. Database Development
For database development, the understanding plant-Environment relationship is critical. Data was collected from various sources including universities and research companies, which is appropriately referenced in relevant sections. Environmental factors have a direct impact on plant’s health, therefore, will act as input variables in the analysis. The database structure is shown in Figure 6. Though, at this point, only five factors: temperature, irrigation, nutrients, light and spacing are analysed.
The database has following three main components: environmental factors; plants’ attributes; and plants’ environmental requirements. The requirement depends on the type and growth stage of the plant, and factors are interrelated: any variance in one may vary other factors. Environmental factors for a seasonal tomato crop over its lifespan are analysed in the following sections.

3.1.1. Environmental Factors’ Analysis

a) **Temperature:** Temperature is one of the most important factors to influence plant growth [90]. Figure 7 shows temperature requirements for warm summer tomato crop [2], which is a member of Solanaceous crop family. The growth level is a theoretical assigned value ranging from 0 (no growth) to 1 (perfectly normal). The Figure also shows that the optimum temperature is 80. Plant health and fruit production can be caused if the temperatures are too high (above 90 F) or too low (below 55 F) [90].

![Figure 7 Temperature requirement for Tomato crop](image)

b) **Irrigation:** Two different terms are used for irrigation, and it is important to distinguish between crop water requirement and crop irrigation requirement. The crop water requirement (CWR) is the amount of water used by a crop for cell construction and transpiration, while the irrigation requirement (IR) is the amount that is provided during irrigation to ensure that crop receives the required amount of water (CWR) [91].

The net irrigation can be estimated using following equation:

\[ IR_n = ET_c - (Pe + Ge + Wb) + LR_m \]

*Equation 1*

Where:

- \( IR_n \) = Net irrigation requirement (mm)
- \( ET_c \) = Crop evapotranspiration (mm)
- \( Pe \) = Effective dependable rainfall (mm)
$Ge = \text{Groundwater contribution from water table (mm)}$

$Wb = \text{Water stored in the soil at the beginning of each period (mm)}$

$LR_{mn} = \text{Leaching requirement (mm)}$

In the current situation, as it is a controlled environment system, therefore:

$Pe$, $Ge$, and $LR_{mn}$ are not affecting plants directly, hence, are ignored. Subsequently, the only contributing factors are $Wb$ and $ET_c$. The amount of water stored in the soil can be measured by using different methods that are available in [91], which are not in the scope of this research; or if the growth medium is other than soil. Therefore, the only factor that needs measuring is $ET_c$, and at this point, this is the only factor that is considered and will be measured. Considering all constants and ineffective factors, equation 1 can be written as

$$IR_n = ET_c \quad \text{Equation 2}$$

And $ET_c$ can be measured by using following equation.

$$ET_c = K_c \times ET_o \quad \text{Equation 3}$$

Where:

$K_c = \text{Crop evapotranspiration coefficient}$

$ET_o = \text{Reference Crop evapotranspiration (mm/day)}$

On the other hand $K_c$ varies from crop to crop and stage to stage, details are available in [92]. However, as a case study, as seasonal tomato crop is selected as a reference and its $K_c$ value is shown in Figure 8, whereas for soilless CEA, $ET_c$ estimation can be studied in [93].
“life is days” represents the overall life span of a seasonal tomato crop. Now, $ET_c$ can be estimated using Equation 3 where the average values of $Kc$ for humid environment are used to estimate $ET_c$ for tomato crop. However, these values depend on environmental conditions, for example, [93] results showed that $K_c$ value was almost equivalent to 1, which makes $ET_c = ET_0$. However, both conditions meet Equation 2; $IR_n = ET_c$.

c) **Nutrients:** Nutrients are another critical component for plants and their uptake for seasonal Tomato crop is shown in Figure 9. Although there are minor nutrients as well, however, at this stage, we are only considering macro nutrients. For example, oxygen is the first nutrient that a seedling requires to germinate. However, that is present in the air. The data shows that Potassium has the highest percentage followed by Nitrogen. In contrast, Potassium is the least required nutrient. However, it is the most important during the initial stage of plant’s life.
d) **Light**: Light is an essential component for photosynthesis [2], and in the absence of light this process stops and plants breathe like humans. The photosynthesis rate will be higher if a plant receives more sunlight but up to a limit. The typical light duration is between 10 to 12 hours [94, 95]. If low light plants are moved to a bright location, the sun will scorch the leaves. Over time, as the wax content on leaves increase, they will become more sun tolerant. Light requirements for various conditions are shown in Figure 9.

For Tomato, the light requirement is 20-30+ mol/m²/day [96, 97] (equivalent to 1157 to 2319 foot-candles). This amount can be provided in a greenhouse by using both natural and artificial
light sources. Although, these conditions depend on the geographic location and vary from location to location. However, the minimum required amount of light can only vary for different species of the same plant.

\(e\) Spacing: Space can affect crop growth and yield, so it is important to leave the appropriate space between plant to plant and row to row. Usually, crops require more space between rows compared to between plants. For instance, tomatoes require between 24-26 inches plant to plant and 24-48 inches row to row spacing and could be cultivated in a square [89, 98].

Although, all factors have an impact on plant, however, the two most important environmental variables for seedling germination are temperature and water [95-99], and the impact can be better understood using simulation and sensitivity analysis.

3.1.2. Simulation and Sensitivity Analysis:
The entire life span of a plant can be simulated under various environmental conditions, however, for now, only germination stage is considered, which can be regarded as a pre-initial stage of plant life. Over last two decades, the growth of computer resources has helped scientist and researchers to develop plant growth models efficiently [94]. The very basic concept of computer simulation of plant growth is discussed in Jaeger and De Refeye [104]. Advanced level of modelling at various stages are reviewed by Prusinkiewicz [105], and they mentioned that the simulation modelling is new, yet becoming a fascinating area of research. Merks, Guravage [106] discussed plant modelling using Virtual Leaf software. The article may be referred for detailed review around the virtual modelling of plants’ architecture. These tools mainly integrate various disciplines like applied mathematics, life sciences, environmental sciences and computer sciences. The focus of this section of the project is to simulate and analyse the impact of environmental factors on seedling germination stage. Theoretical impact values are assigned to simulate the impact of environmental factors. Table 2 shows theoretical impact values for above mentioned 5 factors that might have a minor or severe impact on the plant during its germination stage.

<table>
<thead>
<tr>
<th>Input factor</th>
<th>Factor Impact value(F)</th>
<th>Random Number (RN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>0.38</td>
<td>1</td>
</tr>
<tr>
<td>Water/Irrigation</td>
<td>0.36</td>
<td>0.784237182</td>
</tr>
<tr>
<td>Light</td>
<td>0.04</td>
<td>0.938496496</td>
</tr>
<tr>
<td>Nutrients ((O_2))</td>
<td>0.20</td>
<td>0.569366925</td>
</tr>
<tr>
<td>Space</td>
<td>0.02</td>
<td>0.370168586</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

All impact values are assigned based on their importance for germination, which can be found in [95-98]. The simulated effectiveness of factors is estimated by Monte Carlo Simulation,
whereas the sum of environmental factors impact value is approximately 1. The theoretical germination time \((G.T)\) can be calculated by the following equation.

\[
G.T = \text{Min. Time} + [\text{Lag}] \times [F_1 \times RN_1 + \cdots + F_n \times RN_n]
\]

Equation 4

Lag is the difference between the minimum and maximum time to germinate, which in this case is 3 days. The results are graphically represented in Figure 11.

![Figure 11 Graphical distribution of input risk factors](image)

Results show that there is a 90% probability that seeds will be germinated between 7 to 9 days. The minimum value represents ideal conditions, and the optimum duration will be 6 days. However, all values are assumed to be within minimum and maximum required for the process. As a consequence, the coefficient value of input factors is decreased because it does not have any influence on the minimum duration, as shown in Figure 12. Similarly, coefficient values show their minimal impact on the germination time. However, if these conditions vary, the germination time may rise to 10 days, which proves the scenario of maximum germination duration.
Sensitivity analysis is carried out to analyse the impact of any change to environmental factors, which are temperature, water, light, nutrients and space, and are affecting the germination duration. Figure 13 shows the percent change in environmental factors and their impact on the germination duration. Figure 13(a) represents the percent input change of variables and their effects on the germination mean duration. If the temperature is considered, it is affecting the germination from the very start and stays until the end of germination; while light has the minimum impact on the process. A more comprehensive way is to represent any change in environmental factors and represent it accordingly, and Figure 13(b) shows that relationship between input and output values. Results also demonstrate the relationship between percentage change of environmental factors and mean of germination duration. For negative change value, the average duration is reducing, and for positive, it is increasing. Evidently, the temperature has the highest impact on the process.
Plant-Environment analysis showed that plants have a strong dependency on their environment. Besides, it also revealed that their relationship modelling is complex but can be simulated. However, this basic relationship information is not available on building designing
platforms that could help designers through the process right design for a building integrated agriculture or greenhouse. Therefore, the subsequent sections are focused on the development of the integration of building and plant data to a single platform, which has been referred as Building Integrated Agriculture information modelling (BIAIM).

3.2. Visualisation and UI Development

Visualisation has a major role in simulating the impact of environment on plants. For libraries and user interface development, Horticultural Classification of plants is selected, as shown in Figure 14, and the code sample is given in Appendix A. Autodesk Revit is chosen as a BIM platform to host the plugin. Revit has bi-directional open database connectivity, which makes it more versatile to manipulate the data even outside the BIM environment. Developed concept plugin has all environmental factors, which are discussed in section 3.1, and the data is saved to the local database on the computer. Figure 15 shows two different views of the UI: Revit Plug-in; and plant library and real-time environmental properties. As neither Revit (BIM) nor developed database has plant information libraries, therefore, every time a new plant is created or loaded into the database, it requests for physical and environmental attributes to be uploaded. However, once the information is provided, it is saved to the database and would not be sought if the same species are placed at another location within the project.

![Figure 14 Building Horticulture plugin BIAIM](image-url)
3.3. Database-BIM Integration

The project aims at the integration of BIA and BIM systems. A conceptual BIA database is developed because Revit (BIM) database cannot be manipulated to store the environmental factors and their impact on plants. In this case, BIM model hosts the client database, and all information is saved onto the developed database. With respect to that, the user interface helps to store and retrieve all the data, while database uses BIM environment for management and visualisation purposes.

The link between two databases can be done using objects unique IDs (UID). However, Revit does not have the ability to authorise the database manipulation using plant’s UID. In this case, one of the possible solutions is to link the object libraries using their names. In that way, once a plant is loaded to the user database, the software checks provided a real-time condition on the application and will place the plants accordingly or generate warnings if the conditions are not suitable for plants. For example, Figure 15 shows that the software distributed tomato plants on a raised bed considering the available conditions. 52 plants are placed considering the available space. The red colour is due to the incompatible floor type, as the required medium is soil, but the selected medium is concrete.

4. Discussion

The agricultural industry is not only facing significant challenges at present, but its future is also very demanding. Meeting these challenges with the limited available resources is a current major challenge [107]. Whereas current methods are focusing on genetic stimulation, fertilisation, etc. [108]. Nonetheless, these techniques can only improve yield to a certain limit; while the increasing urbanisation and population challenges are more than just yield.
Therefore, researchers and governing bodies are emphasising the need for new techniques and methods to meet these challenges [109]. As an alternative, the urban farming concept has re-emerged and gained significant attention [110]. Though, in urban regions, due to limited space, BIA is a viable option [14]. While there are no available tools to have P-E relationship information to design such facility. However, BIM tools have the potential to design such building and support through the entire process [24, 73]. The present research investigates BIA and BIM integration. The integration will facilitate the development of a novel system and assist designers and planners to the state of BIM currently.

In this study, we analysed five environmental factors (temperature, water, light, macronutrients and spacing) that affect plants’ life. The research also showed that BIA could help to save a considerable amount of resources; for example, irrigation losses are minimum in a CEA where there are no leaching requirements. However, as there is no direct ground water contribution or rainfall (for CEA crops), which indicates complete reliance on irrigation. The sensitivity analysis showed that a seedling would be germinated between 6 and 9 days; however, there is 90% probability that the seeds will germinate before day 8. While under optimum conditions germination duration is 6 days [111]. The study has shown that a database containing environmental factors can be developed and linked to BIM tools. In this case, Autodesk Revit is used, and linking is done using object’s name as Revit does not support UID [112]. The object shared the properties of both databases: BIM to host plants; developed a database to correspond to the environmental factors.

BIM tools have effectively been used for planning, asset and space management, maintenance [33]. Like any other building, an agricultural building also contains these elements. Therefore, BIM is a powerful tool to design and manage BIA facility throughout its life. Though BIM and BIA integration have not been discussed in literature; however, its potential and demand exist; for example, BIM-based agricultural facilities [34, 54, 57, 105] will be difficult to design, manage and maintain in the absence of plant database. Though the database is developed, however, analyses are limited to five factors. In addition, the database is only compatible with Autodesk Revit. The main limitation of the research is the requirement of the environmental factors, which can only be added to the developed database; not BIM database. Furthermore, it does not consider the real-time data integration at this stage. However, the plugin could be integrated with the sensors to capture real-time environmental data. Although the study only considered tomato crop; any other crop or plant can be added to the database. The development can considerably contribute to BIM level 3 and beyond; and to BIA information management. The plugin is of direct practical relevance and application.

5. Conclusion and Future work

This paper has presented a novel approach to integrating BIA to buildings using BIM design and management tool by developing a plugin. Results indicate that BIA and BIM can be integrated using database development and assigning computer readable rules. This further can be utilised for automated rule checking for optimum environmental conditions. New platform and method were developed to automatically analyse environmental conditions for plants in a BIM-integrated environment, which has successfully been integrated. The performed research
illustrates that BIA planning can effectively be done with the help of BIA-BIM integration. Analysis showed that there would be less waste of resources, e.g. water, nutrients in a BIA, and other factors like temperature and light can be managed effectively using both natural and artificial lighting. Similarly, sensitivity analysis showed that growth could be optimised by providing an optimum condition. This tool differs from existing approaches in that it will engage many stakeholders from designers to facility managers who are involved in the design and management of that facility. Especially, it will help designers and planners at an early stage to design BIA facilities using BIM smart designing tools, which already have proven its benefits to the AEC industry.

This paper is a part of an ongoing doctoral research. Future work will entail the detailed development of software, testing and validation in real-time conditions, and evaluation which will stimulate all environmental factors and their impact on plants in real life conditions.

References


30. Singh, I., BIM adoption around the world: Initiatives by major nations, in Geospatial world. 2017, Geospatial world.


Appendix A

User Interface Code View

```csharp
/// Interaction logic for PlantLibraryUI.xaml

public partial class PlantLibraryUI : Window
{

    // Properties
    IList<PlantData> PlantInfo { get; set; }
    Type ClassificationContext { get; set; }
    PlantData CurrentPlantData { get; set; }

    enum PropertiesContext { LocalDatabase = 0, UserDatabase = 1, AddDatabase = 2, EditDatabase = 3, Navigation = 4 }


    public PlantLibraryUI(IList<PlantData> targetPlantInfo)
    {
        InitializeComponent();
        PlantInfo = targetPlantInfo;
        ClassificationContext = typeof(Model.PlantClassification.HorticulturalClass);
    }

    private void PlantLibraryWindow_Loaded(object sender, RoutedEventArgs e)
    {
        lstClassification.ItemsSource = CreateClassification();
        PropertiesContextChange();
    }

    private void PropertiesContextChange()
    {
        if (EditMode == PropertiesContext.Navigation)
        {
            btnDataBaseInteraction.IsEnabled = false;
            btnDataBaseInteraction.Content = "Select Plant";
            btnDataBaseInteractionCancel.Visibility = Visibility.Hidden;
            ToggleAllPropertiesPanels(false);
            ToggleEditMode(false);
        }
    }
```
```java
public interface IHorticulturalClassification
{
}

[Serializable]
static public class HorticulturalClass
{
    static public IHorticulturalClassification GetHorticulturalClassification(object targetHortClassObj, bool literalType = false)
    {
        if (targetHortClassObj == null)
        {
            return new NotClassified();
        }

        string fullName = targetHortClassObj.GetType().FullName;
        if (literalType)
        {
            fullName = targetHortClassObj.ToString();
        }

        if (fullName.Contains("Edibles"))
        {
            if (fullName.Contains("ColeCrops"))
            {
                return new Edibles.Vegetables.ColeCrops();
            }

            if (fullName.Contains("Legumes"))
            {
                return new Edibles.Vegetables.Legumes();
            }

            if (fullName.Contains("Solanaceous"))
            {
                return new Edibles.Vegetables.Solanaceous();
            }
        }
```