A MODEL BASED ON OCCUPANT MOVEMENT ANALYSIS FOR SPATIAL LAYOUT EVALUATION

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by
Lâle BAŞARIR

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İZMİR

We approve the thesis of **Lâle BAŞARIR**

Examining Committee Members:

Assoc. Prof. Dr. M. Emre İLAL
Department of Architecture, Izmir Institute of Technology

Prof. Dr. Serdar KALE
Department of Architecture, Izmir Institute of Technology

Prof. Dr. Sinan Mert ŞENER
Department of Architecture, Istanbul Technical University

Prof. Dr. Birgül ÇOLAKOĞLU
Department of Architecture, Istanbul Technical University

Assoc. Prof. Dr. Ahmet Vefa ORHON
Department of Architecture, Dokuz Eylül University

6 July 2018

Assoc. Prof. Dr. M. Emre İLAL

Supervisor, Department of Architecture

Izmir Institute of Technology

Prof. Dr. Şeniz ÇIKIŞ

Head of the Department of Architecture

Prof. Dr. Aysun SOFUOĞLU

Dean of the Graduate School of Engineering and Sciences

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ABSTRACT

A MODEL BASED ON OCCUPANT MOVEMENT ANALYSIS FOR SPATIAL LAYOUT EVALUATION

Comparing architectural designs and measuring level of success is rather difficult. This research suggests that monitoring occupant behavior helps extract objective data that can then be interpreted as a measurement for evaluation of space. Lack of occupant behavior tracking and its understanding in terms of spatial layout problems constitutes the gap that underpins the major motivation for this research. The main concern of this research is to build a platform for acquisition of objective data for spatial layout evaluation and interpretation of acquired data to better understand how space is utilized by occupants. The methodology constructed in this research outlines a process for capturing and analyzing space utilization information. Through this process, assessments based on objective data will be available for spatial layouts. The Trajectory Data Processing Framework (TDPF) is constructed to function as a foundation for building connections and correlations between trajectory analysis and problems associated with spatial layouts. A set of tools for analysis of occupant interaction with layouts called Occupant Layout Interaction Analysis (OLIA) is laid out with computational tools and practices.

Keywords: *Building performance, spatial layout evaluation, tracking occupant movement, trajectory data analysis*

ÖZET

MEKANSAL DÜZEN DEĞERLENDİRMESI İÇİN KULLANICI HAREKETLERİNİN ANALİZİNE DAYALI BİR MODEL

Tasarımları karşılaştırmak ve başarım düzeylerini ölçmek oldukça zordur. Bu araştırma, kullanıcı davranışlarının izlenmesinin, mekânın değerlendirilmesi için bir ölçüm olarak yorumlanabilecek objektif verilerin elde edilmesine yardımcı olabileceğini ileri sürmektedir. Kullanıcı davranışlarının, takibi ve mekânsal düzenlemelerdeki problemler ile olan ilişkileri üzerine çalışmaların eksikliğinden kaynaklanan boşluk bu araştırma için ana motivasyonu oluşturmaktadır.

Bu araştırmanın temel kaygısı mekanın sakinleri tarafından nasıl kullanıldığını anlamak üzere mekansal düzenin değerlendirilmesi ve yorumlanması için objektif veri toplayıp işleyebilen bir platform oluşturmaktır. Tanımlanan yöntem, mekan kullanımına dair bilgilerin edinilmesi ve analiz edilmesi için bir süreci özetlemektedir.

Bu süreç, mekansal düzenlemeler için objektif verilere dayalı değerlendirmeleri mümkün kılarken, süreci desteklemek üzere Gezinge Veri İşleme Çerçevesi (TDPF) geliştirilmiştir. Bu çerçeve, gezinge analizleri ile mekânsal düzenlemelerin problemleri arasındaki bağıntı ve korelasyonları araştırmak için bir altyapı görevi görmektedir. Bu çerçevenin doğrulanması için, kullanılabilecek somutlaşmış örneği olarak, kullanıcının mekan düzenlemesiyle etkileşiminin analizine yönelik bir dizi hesaplamalı araç ve işlem barındıran Kullanıcı Mekan Etkileşimi Analizi (OLIA) adında bir yazılım geliştirilmiştir.

Anahtar kelimeler: Bina başarımı, mekansal düzen değerlendirmesi, kullanıcı davranışının izlenmesi, gezinge verisi analizi

To my beautiful little sponsors, Berrak Su and Irmak Su, who donated much of their mommy time to this work,

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CHAPTER 1

INTRODUCTION

1.1. Background

Architectural practice deals with creating spaces to meet occupant needs. The spatial design phase is an “iterative refinement of both form and function until some harmonious coexistence emerges” (Akin, O., 1978) However, the “refinement” phase reaches an end before the building is occupied. The tacit nature of knowledge (Woo, Clayton, Johnson, Flores, & Ellis, 2004) utilized in design makes comparing designs and measuring level of success rather difficult. Hence architectural practice does not emphasize juxtaposition of design intent with the resulting plan layout to fit occupant’s needs. It is also difficult to determine whether design objectives are set to serve the improvement of occupant experience of spaces. A quantifiable evaluation feedback is necessary for measuring the success of design.

All stakeholders of the built environment are expected to take occupant satisfaction into consideration when creating spaces. Building performance research has determined many quantifiable criteria (thermal, lighting, energy efficiency, etc.) along with multitudes of simulation tools to support the design process. Once the construction is complete, Post Occupancy Evaluation (POE) questionnaires can capture subjective evaluation by occupants. The subjective evaluation scores, combined with objective measurements are used to determine how far thermal, acoustic and visual comfort goals are achieved. However, there is a lack of objective measures for evaluating plan layouts. (Leaman et al., 2010) Quantitative plan layout evaluation, is still severely limited.

Over the last few decades, there have been numerous studies that formed the basis for research on spatial configurations. One of the major branches of related research is Space Syntax. This domain of knowledge has been successful in developing analytical tools and theories for understanding and evaluating space. Space syntax has its roots in topological analysis of space rather than dimensional. Therefore, the analysis and interpretation of space is based on occupant vision and accessibility as well as nodes and connections representing spaces and their relations with each other and with occupants.

Space Syntax has contributed a significant impact on understanding of space. However, it does not predominantly focus on occupant behavior, at least not as much as it deserves. Occupant behavior should be monitored and analyzed in a more elaborate fashion in order to enhance the understanding of space and how people interact with it. Within this research, occupant behavior is considered as a data source for evaluation of architectural space.

The Architecture, Engineering and Construction (AEC) industry works to serve one real client and that one client is the *occupant*. There are many *well designed*, *intricately engineered*, *neatly constructed* and evaluated, *quality spaces* produced every day, but the industry does not have the *occupants' opinion* included in this production(Cross, 2001). Occupant behavior is a reflection of the experience that spaces hold for their inhabitants. It is an equivalent case when design processes are analyzed to understand design intent and design outcome. Designers are not the best describers of how they design and what "good" design is. Instead, they might prefer stating what "not good" design is(Cross, 2001). Therefore, the knowledge in design cognition stays implicit when it comes to *experience*. Similarly, occupant experience in many cases, is not explicit enough to provide meaningful feedback for designers, builders or any shareholder of the AEC industry. By tracking occupant behavior, there comes a possibility to uncover the implicit knowledge that reflects itself in behavioral clues.

1.2. Motivation

Lack of occupant behavior tracking and its understanding in terms of spatial layout problems constitutes the gap that underpins the major motivation for this research. This research path is closely related with architectural practice and researchers thrive to visualize how a new kind of architecture without architects can be in the future.

"The general assumption is that in most cases the architect is an unnecessary and cumbersome (and even detrimental) middleman between individual, constantly changing needs and the continuous incorporation of these needs into the built environment…"(Negroponte, 1975).

Architecture has been in the hands of architects for quite a long time. Definitions of an *architect* have not been the same though. Still, an architect's basic task has been to understand the *context* where an *architectural design* is needed and provide *adequate solutions for identified problems*. This task involves experience (tacit knowledge).

Experience is what made the architect hold his respectful status within communities. However, experience seems to be the main specification that machines are not yet capable of having and utilizing in building new built environments. When this happens, architects will need to look for novel definitions for their profession.

1.3. Problem Statement

Subjective evaluation of space layout can be captured through questionnaires and/or interviews with occupants. However, objective data on how occupants utilize space is also needed for both comparing with subjective evaluations as well as discovering problems and/or improvement potentials with layouts that neither occupants nor facility managers are aware of.

Quantitative evaluation of spatial layouts requires a three-step process:

- Data collection: Occupant movement tracking
- Data analysis: Processing of occupant data
- Interpretation of occupant behavior:
- Evaluations based on criteria.

Data collection can be automated or manual. Space syntax research employs both automated and manual collection of data with two methods: Gate counts and following the path of visitors.(B Hillier et al., 1996) Automated data collection technologies on the other hand are under development. Methods for tracking *thermal*, *visual* and *indoor air quality* are efficiently used for energy efficiency assessment purposes. (Labeodan, Zeiler, Boxem, & Zhao, 2015) Video tracking of pedestrian and vehicular movement is improving. The state-of-the-art technology can even track people's movements in detail by matching data coming from GPS with data acquired from the way they carry their mobile phones and come up with responsible driving scores. Yet, none has been employed for spatial layout evaluation.

With this lack of data collection that describes occupant movements, naturally, the stages of processing of data and interpretation of results do not take place. Yet, for evaluating layouts some performance criteria have already been developed by researchers in some fields. Constraint based criteria are regularly used for layout generation. However, problems with layouts are being analyzed within the scope of *efficiency* in production or commercial spaces, and metrics such as *visibility*, *accessibility*, and *attraction* are utilized (Wineman & Peponis, 2010)

Moving forward, towards a quantitative analysis of spatial layouts, a clear description of occupant movements, and appropriate processing tools for discovering utilization patterns through numeric analysis, aggregation, and summary of occupants' interaction with layouts is required.

Such a research infrastructure will guide the development of automated data collection systems as well as provide future research with the necessary tools to interpret occupant behavior for both identifying layout problems and developing performance criteria for layout design. There are specific problems and indications that this research deals with. They are not limited to the efficiency of space but are related with the *quality of occupant experience* extracted from *occupant navigation* through space. Such focus on occupant navigation requires a clear definition of data format to analyze and determine the types of layout problems together with their indications. Observation of behavioral indications on trajectories and corresponding actual behavior patterns list (Table 1) displays the concentration and motivation of this research.

1.4. Aim

This research aims to develop a computational framework for analysis of occupant movements in the context of spatial layout evaluation. The framework defines a representation for occupant movements that can be utilized by data collection schemes – manual or automated - and provides a number of analysis tools for processing collected data. The overall goal is the development of a research platform for supporting efforts on quantitative evaluation of space layouts.

1.5. Methodology

Before a framework can be developed it is crucial to define when and how it will be used. For this purpose, this research first proposes an overall methodology for evaluating layouts that stresses the demarcation between computation of data and interpretation of data. The framework is developed as an infrastructure for quantitative analysis of occupant movements. Throughout the research these movements are represented as "trajectories". A spatial trajectory, according to Zheng is, *"a trace generated by a moving object in geographical spaces, usually represented by a series of chronologically ordered points, e. g.* $p1 \rightarrow p2 \rightarrow \cdots \rightarrow pn$*, where each point consists* *of a geospatial coordinate set and a timestamp such as $p = (x, y, t)$"* (Zheng, 2015). This definition of a *trajectory* is adopted for this work.

The framework provides trajectory processing mechanisms developed as a set of tools in Grasshopper, a visual programming environment integrated with Rhino 5 which is a 3D modeling software by Robert McNeel and Associates. The toolkit is made available as a Grasshopper plug-in and can be extended by future researchers.

1.6. Scope

As mentioned previously, this research is an attempt to address the issue of evaluating plan layouts based on occupant behavior. *Occupant interaction with space* is an important element for gathering feedback on quality of space. How the occupant responds to the layout of the space, needs to be tracked and analyzed to evaluate this interaction. Therefore, this research accumulates its efforts to understanding occupant behavior from traces they leave in the spaces of habitation. The traces in concern are trajectories that occupants create during their interaction in space layouts. These traces are considered as indications of occupant behavior due to their response to layout designs. This response may as well be positive. However, the focus of the research is locked on defining common layout problems that can be analyzed through observing and processing occupant movements.

Elements of a spatial layout that can be considered in its analysis can be classified into four layers (Figure 1). The lowest layer holds elements that are related with the *environmental context*. These include orientation, environmental aspects, etc. and they are defined mostly by design decisions at the building level. Second layer is named *fixed elements* and it spans all elements such as walls, openings, entrances, exits that would require refurbishing in order to reorganize the spatial layout. The third layer contains *flexible elements* such as furnishings that can be moved and rearranged within spaces. The top layer is for the occupants. Although it could be argued that occupants are not an element of spatial layouts, it should be considered that especially in crowded spaces they are an important element that guide design decisions and many building codes and standards. Therefore, occupants that utilize a space should be considered to be a part of that space. This research is focused on the *occupant* layer. This layer holds b*ehavioral interpretations* that can be observed and evaluated through occupant layout interaction analysis.

Table 1. Examples of Trajectory Data Interpretation.

Indication in Trajectory Data	**Observed Occupant Behavior**
Too many trajectories through a zone compared to others	Accumulating at a certain zone
No trajectories through a zone	Avoiding certain zones
Changing trajectory direction with sharp angles	Interrupted Navigation
Changing pace during navigation	Changing pace during navigation
Overlapping trajectories	Bumping into each other within an adequate space
No stops or deviation in Smooth trajectory lines or Curves within the observed layout	Transiting through the space
Inconsistent trajectory, loops, backtracking etc.	Wandering as if looking for something rather than heading towards an end
Unexpected crowd in certain zones	Unintended usage
Changes in routes due to new layout organizations	Occupants wanting to change furnishing layout frequently
Either no step counts or too many compared to other zones	Uncomfortable and/or cannot focus
_	Unease; Sweating, or cold, or too bright or too dark

Specifying which elements of spatial layouts should be considered, and classifying those elements in terms of layers of spatial layout evaluation are important phases of this research. For example, *flexible* and *fixed layout* elements are considered in different layers than the elements of *occupant navigation.* Although the *flexible* and *fixed layout* elements determine majority of occupant movements, quantification of the interaction of occupants with those elements remains unspecified so far. Therefore, *TDPF* is a step towards this goal.

There are several layers to evaluating spatial layouts in built environments. A spatial layout evaluation layering vision for the positioning of this research helps define and display these layers. Trajectory data that is analyzed in this research creates one of the several layers that build up the performance data retrieved from spaces. This layering helps sort and define space and its elements to help construct the Trajectory Data Processing Framework (TDPF).

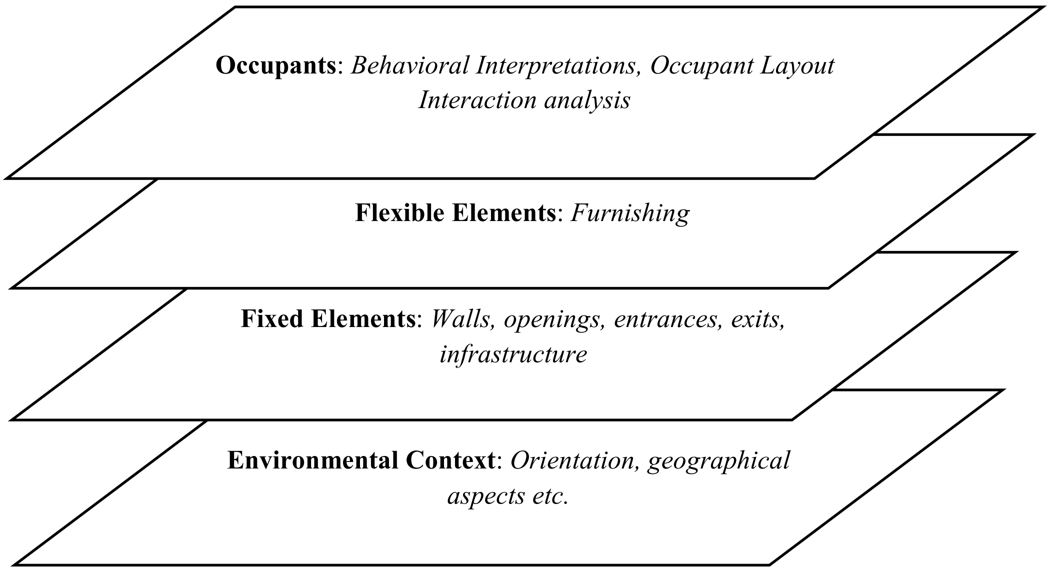


Figure 1. Layers of Spatial Layout Evaluation

The definition of trajectory in this research is very close to Zheng's except for the trajectories having the z-dimension included in *point coordinate definitions*. In *TDPF*, coordinates for trajectory data are recorded as two-dimensional, thus contain x and y's as representation of location data. Third dimension of movement is left out of scope and is not recorded for analysis.

1.7. Outline

Following this introduction chapter, in the second chapter, a summary of related literature is presented. Chapter three first introduces the Spatial Layout Evaluation Methodology with its data acquisition, organization of data, and analysis phases. Then, chapter four specifies the Trajectory Data Processing Framework (TDPF) that accompanies the methodology, and finally it describes a proof-of-concept implementation of the framework, the Occupant Layout Interaction Analysis (OLIA) plug-in for Grasshopper. The fifth chapter presents three case studies exemplifying the utilization of the framework. Chapter six provides a final view of the work along with a future vision that has been the driving force throughout the whole research.

CHAPTER 2

LITERATURE REVIEW

2.1. Overview

This chapter summarizes research focusing on Space, Spatial Layouts and several intersecting domains. Since the research requires a domain-wise extensive scanning of all literature that intersects the framework at different scales, the content of this chapter displays research from a wide range of domains. Architectural space definition and Spatial Allocation Problems and main approaches in space planning are reviewed. Therefore, *topological* or *geometrical* levels mostly referred to in space planning practice are explained. When topological and geometric levels are the case, constraints that determine the output for spatial layout generation are meant. Similar principles apply for evaluation of those spaces. This is the reason why this research includes extensive research in layout generation practices either automated or manual.

Upon definition of space and allocation problems in spaces, the chapter defines another major domain called *Building Performance Evaluation* (BPE). BPE is a huge area of research that provides feedback on various aspects of space use. A considerable amount of literature has been published on BPE and its areas of impact though it is mentioned in this review in accordance with its relevance to the structural basis for the framework that this research constructs. Similarly, research on *spatial layout evaluation* and emergent new concepts and technologies within the same domain are briefly mentioned.

Much of the recent literature on research concerning space use analysis belongs to the domain called the Space Syntax. Therefore, this domain is reviewed as widely as possible throughout the whole chapter when appropriate. Likewise, machine learning applications are mentioned throughout the sections of expert evaluation and current practices for observation of occupant behavior, pedestrian simulations and path planning applications. Observation of occupant behavior focuses on tracking methods and present technologies that capture and display moving images and convert them into digital data. Furthermore, trajectory data analysis applications are mentioned within the scope of this research domain.

Ultimately, although research seems to agree that there is a certain need for evaluation of occupant's interaction with space, there has not been a specifically convergent study on how this should be done.

2.2. Design Expertise

Architect-less-ness, a definition coined in this dissertation for a new kind of architecture is not a new vision in architectural discourse. It is a vision that finds its roots dating back to 1960's if not earlier. There was an appeal to grasp the design process of architects and implement it into architecture machines. This meant shifting the architectural design expertise from professionals to occupants or to *anyone* who could use those machines. (Negroponte, 1975) Other intensive research on design cognition and computer human interaction has been done to understand whether machines can design.(Cross, 2001) One experiment was done on comparing performances of humans, machines and human-machine interactions in coming up with good layout design suggestions. The experiment revealed frustrating results for researchers at the time of the study leading them to resign from the determination that machines could design as good as or better than humans. However, as computing capabilities and machine learning principles have gradually improved, Cross came up with new research methods to identify design processes in humans and their implementation in artificial means. This more recent research involved understanding the way humans conduct design processes. Expert designers were asked to reveal their ways of judging *bad design.* Rules were set based on designers' claims and machines were trained to use them in their own judgements. The results were consistently satisfactory on machines' side even compared to human experts. Cross takes this argument as a convincing motivation for research on artificial intelligence. This feedback he gets from design and machine learning domains encourages his belief that humans will learn more on the human behavior and human capabilities while advancing those of machines.

2.3. Defining Space

To clarify the core questions of this research it is essential to define what *space* is. This section presents a review of research containing definitions of architectural space. Metrics, constraints, objectives and/or qualities concerning space and spatial layouts and allocation problems are included.

2.3.1. Space, Spatial Layout

Architects define space in terms of the qualities of the built environment that shape occupant experience. The implicit knowledge that forms the basis of layout design by the professional planner has been analyzed by several research efforts that refine the definition of space, spatial layout and related terms. (Key, Gross and Do, 2008) By implicit knowledge, researchers mean experiential qualities of space and refine definition of space down to *enclosure*, *viewfield* and *continuity.* The study defines *enclosure* as a location that is enclosed by architectural elements, *viewfield* as the vision a viewer has from where she/he stands within that space, and *continuity* as the flow between spaces through architectural elements.

Liggett defines layout planning activity in terms of assigning certain activities to certain locations. The challenges in this assignment task is generally defined as *spatial allocation problems*. His work classifies layout in terms of underlying problems that form them such as:

- Space as discrete objects
- Space as area
- Space as area and shape

Issues of size and shape is not involved in the layout process definition of *space as discrete objects*. Therefore, *space as area* requires size information and involves matching functions with areas. This is a two-way matching requirement whereas an object may require a certain size or an area might be expected to accommodate certain numbers of objects (inhabitants). The third definition of space involves the required set of activities to be matched with the corresponding shape and size (Liggett, 2000)

Layout definitions and related research were at large done by engineers tackling with facilities layout efficiency. Therefore, it was defined in a manner that prioritizes cost and profit issues over architectural space qualities. A major line of research follows Muther's Systematic Layout Planning (SLP) approach. According to SLP, layouts can be defined by five basic elements – *P (Product), Q (Quantity), R (Routing), S (Supporting Services), and T (Timing)*. In his research Muther suggests that all layout problems rest on two of these basic elements one of which is "Product (or material or service)" that will be produced and the other is Quantity (or volume) that will be produced. Therefore product refers to what a layout should "accomplish" (Muther & Hales, 2015). Though these terms seem to belong to a completely different paradigm of planning, they become much familiar when transferred to the architectural domains.

As stated earlier, research on space and space layouts is not new. A list of authors in space planning domain between 1955 and 1985 is reviewed within the following table (Table 2) to get a glimpse of how study evolved in this domain.

2.3.2. Spatial Allocation Problems

Research around optimal spatial arrangements in buildings spans a history of approximately 60 years. Intense work on algorithms yielding space planning solutions have been concerned with operating efficiency issues as well as laying the ground for many architectural computer aided design software. Finding optimal solutions to minimize the cost of inter-spatial moves within production plants was initially described and formulated as *general quadratic assignment problem* by Koopmans and Beckmann on econometric terms. (Liggett & Mitchell, 1981)

Several applications attempting to solve certain space allocation problems involve facility layouts of large scale buildings for healthcare, education and/or commerce. Although main focus of such research has been the optimization of layouts, there has been work around defining criteria for evaluation and comparison of generated spatial layout options.(Liggett, 2000)

Identification of spatial problems brought about the following questions:

- How can the problem be expressed as a one-to-one assignment problem?
- How should zones and activities be defined?
- How should the cost function be specified?
- What type of travel time data should be used?
- How should interactions between activities be expressed?
- How should fixed costs be expressed?

These questions were formulated in terms of mapping certain facilities to certain locations. Locations were designated as zones and subdivisions within those zones. Travel time data was either expected as input by the planner or was formulated to be calculated in terms of zone dimensions (Liggett & Mitchell, 1981)

Three basic approaches for automated layout generation:

- Single criterion methods: Optimization of layouts is based on minimization of

Table 2. List of Authors on Space Planning, 1955-85
(Source: Lobos and Donath, 2010)

Author	**Title**	**Publication/Reference**	**Year**
Buffa, E.S	Sequence analysis for functional layouts	J.Ind.Eng.	1955
Buffa, E.S., Armour G.L., Vollman, T.E.	Allocating Facilities with Craft	Harvard Business Review	1964
Johnson, T.E., Weinzapfel, G.E, Perkins, J.I., et al	IMAGE: An Interactive Graphics-Based Computer System for Multi-Constrained Spatial Synthesis.	M.I.T.	1970
Mitchell, W.J.	A Computer-Aided Approach to Complex Building Layout Problems	EDRA2 Conference	1970
Miller, W.R.	Computer-Aided Space Planning	Workshop on Design Automation	1970
Eastman, C.E.	A System for Computer Assisted Space Planning	Workshop on Design Automation	1971
Al Banna, S. and Spillers, W.R.	An Interactive Computer Graphics Space Allocation	Workshop on Design Automation	1972
Mitchell, W.J. and Dillon, R.	A Polynomial Assembly Procedure for Architectural Floor Planning	Third Environmental Design Research Association Conference	1972
Stiny G., Gips, J.	"Shape Grammars and the Generative Specification of Painting and Sculpture"	CV Freiman (ed) Information Processing 71	1972
Krawczyk, R.J.	SPACE PLAN: a User Oriented Package for the Evaluation and the Generation of Spatial Inter-Relationship	10^{th} Design Automation Workshop	1973
Gero, J.S.	A System for Computer-Aided Design in Architecture	Principles of Computer-Aided Design	1973
Teicholz, E.	The Computer in the Space Planning Process	12^{th} Design Automation Conference	1975
Gero, J.S.	Computer Aids to Design and Architecture	N. Negroponte (ed)	1975
Weinzapfel, G., Negroponte, N.	Architecture-by-yourself. An Experiment with Computer Graphics for House Design	Siggraph	1976
Fortin, G.	BUBBLE: Relationship Diagram using Iterative Vector Approximation	15th Design Automation Conference	1978
Ruch, J.	Interactive Space Layout: A Graphic Theoretical Approach	Conference on Design Automation	1978
Shaviv, E.	Automatic Generation of Optimal or Quasioptimal Building Layout	CAAD Futures	1985

costs due to relational functions such as flow or communications among activities.

- Graph theory based methods: Layouts are created based on adjacency of activities. Activities are represented as nodes and their relationship is the main focus of layout generation.
- Multiple criteria methods: Methods considering multiple constraints based on feasibility, access, light, privacy etc. These methods follow Eastman's General Space Planner (Eastman, 1971), and Pfefferkorn's Design Problem Solver (Pfefferkorn, 1972) and a more recent application SEED by Flemming (Flemming, 1999). This path also uses orthogonal shapes and relationships for spatial and relational arrangements. (Liggett, 2000)

2.3.3. Topological / Geometrical level in Space Planning

Space planning requires a set of arrangements for space elements of several relationships, and sizes. Former is called the topological level and latter is the geometrical level. Topological level is similar to a bubble diagram and geometric requirements of the problem provides the basis for the geometric level. Topological problems refer to grammars. Shape grammars are based on linguistic composition rules and act as algorithms to produce shapes and spatial designs. Geometrical level is set for dimensioning of spatial designs using optimization techniques based on multiple criteria.(Jo & Gero, 1998) With several software solutions, architects can view and choose among many design alternatives at a topological level and optimization filters suggest best geometric placement solutions. ArchiPlan is an example of constraints based layout generation software.(Medjdoub & Yannou, 2000) Architectural space specifications are set by architects and stored in a functional diagrammatic interface. The software has an embedded hierarchical classification of architectural space. This classification allows for application of relational constrains at topological level. Topological constraints are defined with terms such as adjacency, non-adjacency or proximity of one space to another. An example of a topological constraint for a residential typology is "the *kitchen* and the *living room* are *adjacent* with 1 m minimum for contact length". Topological level solutions are then eliminated due to geometrical level options and optimization algorithms. These definitions and constraints consider architectural space as defined contours of orthogonal shapes/entities.

Another method (Merrell, Schkufza, & Koltun, 2010) of generating building plan layouts from *high-level requirements* uses machine learning and optimization techniques for layout generation. It is highly successful in creating sound topologies and geometries. However, generative methods described in their work do not refer to factors identified by inhabitants during layout generation.

Another layout design optimization model (Michalek, Jeremy, Choudary, & Papalambros, 2002) identified quantifiable aspects for layout design, and integrated design constraints and objectives in their layout generation method. In their approach, they identified problems in evaluating topologies in terms of openness, proximity (of design units), directionality, or symmetry. Their model argued that these qualities required rough geometry to be evaluated even though they were classified as topological. Consequently, they suggested that geometric evaluation of each topology would therefore display topological evaluation of layouts. The discreet optimization algorithm formulated for this method conveys previous information to newer generations of layouts. Topological and geometrical evaluation processes form loops for optimization purposes. Thus, for optimization of geometries and topologies, this method uses design constraints and objectives as listed below:

- Geometric Design Constraints: Force Inside, Prohibit Intersection, Force Minimum/Intersection, Force to Edge, Bound Size, Minimum Ratio Constraint, Build Cost, Feasible Window, Bound Lighting.
- Geometric Design Objectives: Minimizing Heating Costs, Cooling Costs, Lighting Costs, Wasted Space, Access ways, Hallways
- Topology Design Constraints: Overlap Constraint, Connectivity Constraint, Path Constraints, Planarity Constraint, Envelope Constraints
- Topology Design Objective is minimizing the geometric objective value of its topology through a function that employs geometric optimizer *Sequential Quadratic Programming* for any feasible topology

Definition of space based on constraints and/or objectives clarifies the way any research on spatial analysis is designed. In this field, definition of space does not include any aspect of occupant activity. Occupant movement is not considered as a factor that has impact on definition or evaluation of architectural space. Neither is there sufficient knowledge base on how occupancy in terms of navigational patterns should be defined and quantified.

2.4. Observing the occupant

Occupants are simulated in majority of evacuation simulations for buildings. Simulations give verified insights/vision to their users. However, simulations are verified with algorithms that use models for predictions. In simulations, feedback from real occupants is missing. Rather, they rely on algorithms.

Space Syntax research also uses a model for tracking occupant movements. This work focuses mainly on public open space. However, the research group has also employed their methodology in evaluation of architectural space in workspaces, supermarkets, hospitals, museums such as the National Museum and Tate Modern etc. In their methodology, there are three key features(B Hillier et al., 1996). First is the *analysis of angular movement* through which they concluded that movement follows a least angle path. They accept this feature as essential to their modelling approaches. This feature is a reflection of the original basic concepts of space syntax employing *isovists* in their analysis. “An isovist is the set of all points visible from a given vantage point in space and with respect to an environment”(Benedikt, 1979) Isovists change according to the objects' position and sets of isovists and isovist fields form an alternative description of environments. The second feature of their approach is *evaluation of multi-scale activity*. This is the analysis of spatial layouts in terms of both short and long-distance journeys. Different scales of journeys are evaluated simultaneously to reveal how different parts of the same network are differently used, depending on the scale of journey. The third feature is *integration of the spatial, land use and transport factors*.

In another research based on observation of the occupant during three different activity scenarios, space is fragmented to cells(Gómez, Do, & Romero, 2014). These cells are set for spatiotemporal analysis of activity shapes. *Weighted occupancy* is used as a metric and defines the *percentage of time* an occupant stays in a cell. Therefore, the research runs at a defined space, and activities change within that space while conforming to three different activity scenarios. In their study, Gómez et al. observed how occupants in a controlled space- a room designed for observing autism in children- within an academic institution used space in three scenarios: *game scenario*, *coffee scenario* and the *TV scenario*. All scenarios display different levels of *dispersion* and *gravitation* on a grid of cells within the activity space. Results of this study though, are interpreted by the researchers that layout configuration of space is not necessarily the influencing factor for significant differences between activity shapes.

2.4.1. Tracking methods / systems

Technologies to obtain objective data on how occupants utilize spaces have become more accessible over the last decade. Commercial applications are now available for counting and tracking customers at shopping centers and stores. Radio frequency identification (RFID), video cameras, 3D scanners, implants, and biometrics are some of the technologies that are being employed in this field.

2.4.1.1. Video surveillance

In the case of video surveillance, various public spaces, where video surveillance is appropriate, are seamlessly being monitored. Occupants' movements within these spaces are recorded and analyzed through image processing algorithms. Video recordings in public places raises the issue of privacy for people and requires acquiring appropriate permits. One recent research previously mentioned *Activity Shapes* (Gómez et al., 2014) waived the issue of privacy by setting up a lab environment to record human behavior within space. The lab is a facility set up for child study but the participants of this experiment are adults. Since this study collected data in an experiment setting the researchers did not have to tackle privacy issues. The recording was done through overhead cameras. The research is set up for uncovering a pattern formed by human activity and their distribution within space along with their postures; *standing, sitting, and walking*. The search for these patterns also involves temporal data. Therefore, the data is recorded in a video which is then converted with additional analysis (mainly computational) methods into patterns based on the research metrics of the research.

2.4.1.2. Video tracking software

Raw video surveillance outputs contain huge data and need to be processed to be refined for analytical purposes. Video tracking software help us in various domains driven from data analysis. An example of tracking pedestrians (Dehghan, A., et al 2014) uses *tracklets* and track their trajectories (Figure 2).

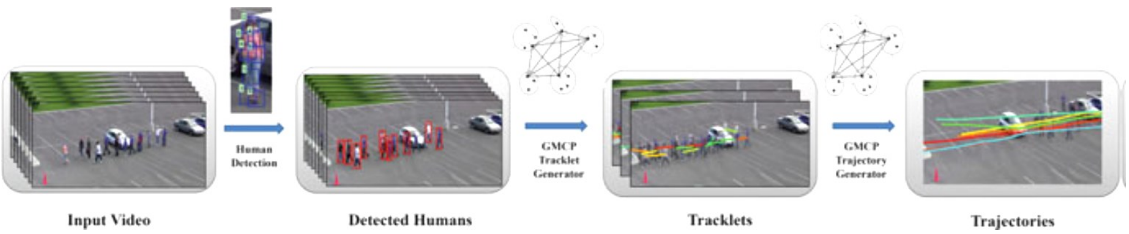


Figure 2. Block diagram of the data association method.(Dehghan, A., et al 2014)

The research group states that they use a method based on "Generalized Minimum Clique Problem (GMCP)" for data association. *BriefCam* and *Axxon* are companies producing commercial analysis tools for clients to spend least time watching their videos. Rather, those applications run algorithms that can analyze multiple inputs simultaneously and therefore give the option to rule time out.

2.4.1.3. Sensors

Tracking movement of people is already a challenge as a data collection method. The information collected is then evaluated for purposes of programming those spaces in order to support users in their daily tasks (Suter, 2015). Another group of researchers worked on analyzing movement (Ong, Wachowicz, Nanni, & Renso, 2010). Their proposed framework aims to mine patterns in terms of their relation to each other and semantic aspects of movement patterns. To obtain this information, they produced data from two different sources. The trajectory data was collected by handing out GPS devices to visitors. The semantic aspects were derived from surveys that included questions such as frequency of visits, the number of accompanying children, of dogs, the main activity of the visitor. Their system includes differentiating the reasons that created the extracted patterns and processing overlapping movement patterns. This was achieved by collecting data on why they chose certain routes.

Besides built spaces, sensors can create a wide range of data on movement of occupants in mobile spaces, that is, when driving. This example is included in this review due to its technological variety and novelty in tracking systems. TrueMotion (https://gotruemotion.com/) tracks drivers' speed patterns, braking habits, which door they get off etc., directly on sensor data. Sensors are embedded in mobile phones and registered through their specific mobile software applications. The app can detect when the phone is in driver's hand or in the car through its identification methods. The reason there are several technologies combined in this system is that *GPS* is more reliable for speed detection where detection on linear force and acceleration with the help of *accelerometer*, or information on rotational accelerations through a *gyroscope* and/or data on pressure sensing system can provide other types of reliable data for understanding drivers' behavior during their navigation on the roads.

Inertial Measurement Unit(IMU) sensors (Jiang & Yin, 2017) also allow data creation for detecting user behavior. The work of Jiang shows that visual tracking of pedestrians can be complemented by sensor signals from IMU sensors. IMU tracking provides data with the help of *accelerometer, gyroscope* and *magnetometers*. While visual tracking through video surveillance data is based on vision, IMU tracking performs tracking even when visual data collection is occluded.

2.4.1.4. Geographical Information System (GIS)

Geographical Information System (GIS) is a broad data management system that can acquire, keep, organize and display data linked with location. Geospatial data operates at a huge scale and is very complex. This type of data needs simplifying into splines, points and surfaces to make it easier to manage. Data preprocessing for spatial data analysis is needed for indoor environments where Global Navigation Satellite Systems (GNSS) do not create efficient data. Occupant tracking during indoor navigation, however needs refinement. (Nguyen-Huu, Lee, & Lee, 2017) Tracking accuracy is improved by combining indoor positioning system called pedestrian dead reckoning (PDR) with wireless fingerprint and map-matching techniques. Results of their study show that a combined method is much more efficient when indoor mapping is improved and smartphone holding styles are defined and interpreted.

2.5. Analyzing Spatial Data

There is huge amount of data constantly generated through the general use of information technologies on devices and through interactions that people use every day. This data is also used for spatial analysis purposes. Preparing spatial data for analysis is another challenge in spatial evaluation methodologies.(Zheng, 2015) For example, data collected needs a process to convert raw coordinate data to road segments. Therefore, each point on trajectory is projected onto a corresponding road segment. This process is called *map-matching*.

Among the many applications of indoor positioning systems are *Radio Frequency Identification (RFID)* positioning, camera positioning, ultra-wideband etc. The *Pedestrian Dead Reckoning (PDR)* technique however, is a more relevant one according to Nguyen et al. (Nguyen-Huu et al., 2017) when indoor localization is the case. It has advantages as to the way it collects data, simply through the sensors embedded in smartphones, however, it makes errors in estimating the next moves or positions. Another technique called the WIFI fingerprint is also a matching algorithm based on reference points that were set offline during training phase and the online phase where the *scanned received signal strength indicator* (RSSI) values are compared to estimate precise location. While WLAN systems facilitate this technique, RSSI does not efficiently serve tracking performances. Therefore, the authors suggest some helping features called *landmarks* that help improve data collection and data processing phases.

Once data is converted into trajectories, analysis phase is the next step. However, this conversion is rather complex and there is huge research within this domain utilizing machine learning algorithms to refine collected data.

2.5.1. Trajectory Data Analysis

Trajectory data analysis is a very broad domain. Trajectory data collected at geographic scales belong to a system called GIS. In his systematic survey into the field of trajectory data mining Zheng provides a detailed overview covering wide variety of tasks for trajectory data management (Zheng, 2015). Trajectory data is required to go through several phases to obtain distilled and plain data to be processed. These phases depend on how and why this data will be interpreted. This phase can be defined as trajectory preprocessing which includes several processes to *filtering, compression, stay point detection* and *segmentation* of trajectory data. The process of *filtering* defines mainly the noise filtering of data from vague instances caused during recording. *Compression* phase reduces data storage to its essential utilities. *Stay point detection* identifies stops on trajectories which correspond mainly to important semantic data. *Segmentation* is for classification and analytical purposes to process data into time intervals, spatial shapes and or semantic meanings.

Another way for exploring the geometry by comparing movement paths is by using prototypical curves.(Sas & Schmidt, 2007) In this study the researchers gather information about the level of spatial knowledge that the occupants acquire within the virtual environment that the study is designed in. *Bézier Curves* are used to analyze the geometries of navigation behavior by computing curve approximation. This work is a good example for deriving quantitative data from occupant movement and interpreting it as information on occupant behavior.

2.6. Evaluating Space

Evaluating space is a broad, challenging task from several aspects. There is wide variety of work focusing on evaluation of architectural space but from different perspectives and with a broad range of concerns. Since architectural space is man-made, it is much more controllable and more suitable for refinement than natural spaces. However, there is a broader understanding and knowledge of natural conditions and how to measure and manipulate them than to evaluate spatial qualities. This subsection reviews spatial evaluation approaches in the field.

2.6.1. Building Performance Evaluation

Building Performance Evaluation (BPE) is described by Preiser and Vischer as a feedback system to maintain building quality throughout the design, construction, occupation and operation phases. (Preiser & Nasar, 2008)

According to Adrian Leaman, Post-Occupancy Performance Evaluation tries to answer four broad questions:

1- How is this building working?'

2- 'Is it intended?'

3- 'How can it be improved?' and

4- 'How can future buildings be improved?' (Leaman, Stevenson, & Bordass, 2010)

Volker Hartkopf also brings its goals down to four major units and lists them as

1- User satisfaction,

2- Organizational flexibility,

3- Technological adaptability, and

4- Environmental and energy effectiveness.

User satisfaction is then branched into six elements; the *thermal*; *acoustical* and *visual environments*, *spatial quality*; *air quality*, and *building integrity* (Hartkopf & Loftness, 1999)

Kalay defines "Evaluation" as the *glue* of three basic activities of design process. The three activities are:

- *Analysis of the problem* and coming up with a set of goals to achieve within the boundaries defined by a list of constraints.

- *Synthesis of one or more solutions* that is believed to achieve the goals bound by the constraints.
- *Performance prediction and evaluation* of proposed solutions in terms of consistency with each other and with the goals that are set to achieve.

Evaluation *guides the generative process, uncovers opportunities and indicates tradeoffs* to ensure and enhance the quality of design solutions.(Kalay, 2004)

A newer research suggests that modern office workers evaluate comfort based on security, building appearance, workstation comfort and overall visual comfort (Adeniran & Akinlabi, 2012). These comparably new assessment criteria are additions to Vischer's seven POE qualities: *air quality; thermal comfort; spatial comfort; privacy; lighting quality; office noise control and building noise control*. POE practices have accumulated vast amount of information due to how building performance should be assessed and how data should be interpreted. However, the use of POE in a feedback loop is not yet common practice as Francis Duffy has argued in his foreword to *Assessing building performance: Its evolution from post-occupancy evaluation* (Preiser & Nasar, 2008).

2.6.2. Spatial Layout Evaluation

Automated layout planning methods have also been finalized in phases that involved evaluation to come up with best solutions among alternatives. Whether automated or not the generated layouts are subject to evaluation so that they are rated and chosen among alternatives.

Facilities layout planning applications has been improved fairly in order to serve for productivity. Therefore, costs and evaluation and comparison of layouts have been based on corresponding factors. There are several applications and models in such evaluation. The following three models display layout analysis models that are used for hypermarkets (Inglay, Park, & Andheri, 2010):

- Mathematical Programming Models: An objective function is assigned a mathematical programming model. This model facilitates optimization for criteria such as *space efficiency, distance traveled, service convenience* etc.
- Queuing Models: Queuing theory helps estimate ratings between alternatives. This model provides feedback based on queuing situations at the elevators, service desks, parking etc.

- Simulation Models: Simulation methods provide a selection of experiments to rate among based on various criteria.
- Spatial Relation Network (SRN)

A number of studies build piles of new knowledge to support evaluation practice. For example, a research on spatial layout structure is developed so that the designer can evaluate spatial performance of a layout within a three-step workflow (Figure 3). This system uses spatial relation network (SRN) metrics for evaluation and creates a multi-view space model to run the evaluation in concern. (Suter, 2015) The views that are used in this system are extracted based on the evaluation concern. Therefore, the system generates multiple views of a certain layout in order to serve this evaluation process. However, this system does not track occupant within this evaluation method.

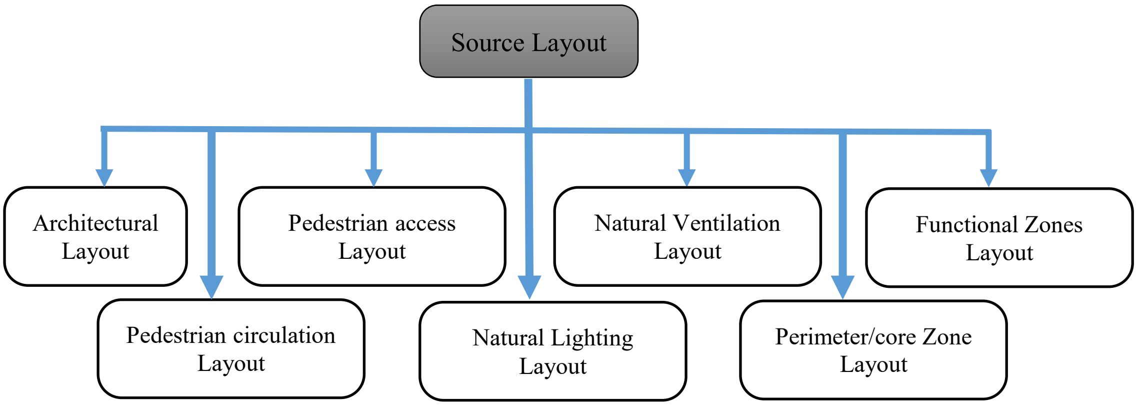


Figure 3. Multi-view space model, Suter, 2015

2.6.2.5. Spatial Quality Indicators

UK Government initiatives and funding programs such as the National Affordable Housing Programme (NAHP) and Affordable Homes Programme (AHP) have come up with design standards to meet for funding bids (The National Affordable Homes Agency, 2008). These standards are set to assure that housing quality can be measured and evaluated not only based on cost but rather, on quality. The housing quality indicator (HQI) system. Along with a complex list of basic requirements spatial quality indicators (SQI) are evaluated and rated. For example, there is a list of *furniture* that are expected to fit in a room and *appropriate activity* and *access zones* are defined. In the case of all requirements being set, a room is rated as meeting a basic standard. Activities are treated the same way as furniture and they are assigned geometric requirements such as minimum space for each occupant for a specific activity and access zones are indicated. Quality indicator system also uses an alternative matrix to enable assessment. The system has assigned a 50% score percentage for qualitative evaluation of living spaces, circulation and storage and safety.

Another evaluation system is introduced in the form of a mathematical model to assess a *good layout*. (Bao, *et al.*, 2013) The researchers challenge themselves with three common shortcomings of such models being too simplified, being based on unrefined parameters and ruling out of visual aspects of design. Therefore, they employ constraints classified as *hard* and *soft*, in order to generate and evaluate layouts. *Hard constraints* are mainly based on building guidelines and classified as:

- Parcel constraints; conforming to building boundary
- Topology constraints; placement/ location of buildings
- Thickness constraints; minimum and maximum thickness of blocks are defined to allow access thus to avoid unreachable areas.

Soft constraints are a set of quality indicators abstracted as energy functions. The lower the energy, more desirable the layout configuration:

- Covered area energy; proportioning covered area with the lot
- Courtyard energy; worked on the inner facades
- Shadow energy, shadowing effect on adjacent buildings
- Heat energy; based on exposed surfaces (Bao et al., 2013)

2.6.2.6. Layout IQ

There is research and a software as an output, called Layout IQ that is used preferably in workspaces, healthcare spaces, and production facilities. Layout IQ is a software that is used in modelling efficient workspaces (Lee, Lee, & Kang, 2013) The software can measure number of trips from an exact location to the place of work or equipment. Layout IQ uses this computation to suggest most efficient solutions. The software is based on several methodologies for data collection. It can be the process routing recording method that identifies the right sequence of the goods flow or equipment flow or a subjective approach that enables data collection through surveying occupants. The latter is applied when trip intensity has less impact than the opinion of people working in that space, e.g. patient room, surgical wards. This research is based on efficiency and flow therefore it has certain stations from and to occupants are frequently travelling. However the tool does not focus on inquiring occupants' navigation patterns as a whole but evaluates trips between stations that are essentially travelled due to the work to be done.

2.6.3. Pedestrian Simulations

Evaluation methods that are linked with occupant/pedestrian navigation are mostly accumulated within computer simulation application and experiments. Agents act as occupants within simulations. That type of work mainly focuses on evacuation systems. A research on planning an evacuation system based on simulation proposes an evaluation system for office layouts. The agents move while deciding on their escape routes based on information regarding the office layout. This information on office layouts include impassable spaces, crowded areas, other agent's actions etc. Therefore, the evaluation criteria include maximum time for escape, average speed and number of agents that could not find the entrance timely (Sato & Osana, 2012).

Although occupant traces are more appropriate for identifying occupant behavior than agent decisions within simulation environments, simulations carry valuable knowledge referring to occupant behavior and evaluation criteria.

2.6.3.1. Wayfinding

Wayfinding rate or quality is very much dependent on the way people explore and discover their environment. Spatial configuration, therefore is significantly important when non-familiar users of that space are the case. Evidence suggests that floor plan layout has the highest rate of influence on occupants' way-finding experiences (Tomé, Kuipers, Pinheiro, Nunes, & Heitor, 2015). Wayfinding behavior, especially in urban environment is perceived by Golledge to be based on various criteria such as shortest distance, least time, fewest turns, most scenic/aesthetic path, first noticed, longest leg first, many curves, many turns. (Golledge, 1992)

Observing the way people navigate, Conroy came to the conclusion that people pick straight lines for reaching their destinations. (Conroy, 2001). In her work on angular deviations in navigation paths it is observed that minor deviations occur when the paths do not lead to where occupants aim for. Otherwise, her conclusion is that the secret to wayfinding for people is to "follow their nose". Occupant navigation, however, is not based solely on wayfinding abilities or on their perceptions of visual space but is a complex phenomenon that needs to be rooted on many aspects of human behavior and the effects of their environment.

2.6.4. Space Syntax

During the search for an evaluation and interpretation method for extracted patterns a similar approach called *Space Syntax* came across. Space syntax research has developed ways to convert spaces into topological relationships. It is a theory and method to uncover the logic of spatial configurations in architectural and urban space. It was developed by Bill Hillier and Julienne Hanson. It is a theory and a method to build a *"descriptive theory of how spatial pattern can and does, in itself carry social information and content"* (Bill Hillier & Hanson, 1984) The space syntax analysis is based on a theory of topological relations, called the *Graph Theory*.

The three most common ways of conversion in concern are convex spaces, axial lines and visibility graphs. The first, convex spaces, is described as when a straight line is drawn between any two points on the perimeter of a space never intersects the perimeter in another location of that space. The second, axial lines, represent the longest paths through space that display the movement potential of an environment. The third, visibility graphs, computes the visibility relationships between squares of a grid laid out on plans. These graphs reveal either sight or movement related properties of those spaces (Dawes & Ostwald, 2013)

Space Syntax research also displays a model of tracking occupant movements. This work focuses mainly on public open space. However, as mentioned earlier in the section on observing the occupant, the research group has also employed their methodology in evaluation of architectural space in a variety workspaces including museums hospitals and supermarkets.

There is research on refining the shortcomings of these methods in terms of analysis phases that are mentioned here. However, the data processing phase is not necessarily serving spatial layout evaluation in terms other than suggesting best *flow of accessibility*, *visibility* or *popularity* of certain zones. Therefore, the work that is carried out in all research methods that are mentioned here brings the notion of combining movement data with semantic data in order to understand movement trajectories and resulting patterns.

Researchers also work on evaluation tools based on Space Syntax methodology. Their system formalizes topological relations with required connections rather than adjacencies. The system retrieves feedback from an initial bubble diagram in the form of spatial performance measures for their analysis. They used space syntax metrics such as *Depth;* distances of nodes from each other, *Integration;* a measure of centrality that reveals whether a certain space is *private* or *communal, Difference Factor*; *Control value* of links between points, *Choice* or *Betweenness;* is a measure of importance based on shortest paths. The creators of this system automated performance analysis. However, the analysis does not yield comparative evaluation among spatial alternatives. The evaluation is not automated and is assigned to human user of the system (Nourian, Rezvani, & Sariyildiz, 2010).

There is research on refining the shortcomings of analysis phases in the methods that are mentioned here. However, the data processing phase is still limited to helping users evaluate spatial layouts in terms of best flow of accessibility, visibility or popularity of certain zones. Therefore the work that is carried out in all research methods that are mentioned here combine movement data with semantic data in order to understand movement trajectories and resulting patterns.

2.6.5. Mapping Navigation and Emotions

Linking evaluation of environmental quality with emotions is another field of research which incorporates and corresponds location information with occupants' feedback. In their methodology they use subjective feedback that they match with their evaluation criteria afterwards (MacKerron, 2012). Participants download the software application (app) called *Mappiness* and agree to report when they are signaled. They are expected to provide feedback on their *mood* on a sliding scale and companionship, activity, time, location type. The researchers then correspond daylight, weather condition and land cover information using GIS and incorporate the GPS information.

2.6.6. Expert evaluation

As previously mentioned there is an accumulation of knowledge and expertise in the field of architectural design practice that is defined to be a type of tacit knowledge. Tacit knowledge is what experts gain through time and experience. Indeed, the expertise that is mentioned here cannot clearly be justified or tested since it is not evaluated objectively. However, this research tries to build a framework that constructs a base for quantifying part of the expert knowledge that has accumulated and inherited through architectural education and experience over a huge course of time.

Some other recent studies have considered the relationship between layout and usage in office spaces. One of these works uses machine learning to come up with predictions on how space layouts will be used. A company that creates workspaces around the globe is training its machine with a learning algorithm (Artificial Neural Network (ANN) in this case) to understand the usage patterns of meeting rooms and other specific spaces and predict their usage to help design new layout organizations. (WeWork Offices 2017) Although the expertise of architects is revered by the users of this machine experts, it can be anticipated that the field of architectural design will soon be dominated by these artificial experts. These experts will be doing specific evaluations that can then be fed back into the design phases of spatial layouts.

2.7. Summary

As mentioned earlier, the research fields linked with evaluation of spatial layouts are many and scattered. Despite the efforts to keep the background research narrow and focused, the base that this research in built upon is wide.

Main approaches in space planning and architectural space definition as well as *topological* or *geometrical* levels mostly referred to in space planning practice are explained. Cases concerning observation of the objects of tracking are presented. Methods used for analysis purposes and spatial evaluation practices are reviewed. Also the review demonstrates that spatial evaluation research is mainly clustered around either subjective feedback from occupants or simulation applications where there is no real occupant involved if automation is involved.

Based on this review there is a gap in research on these two areas.

- A methodology to analyze occupant navigation within and interaction with spatial layouts.
- A framework that holds a structure for understanding links between occupant behavior and evaluation of space.

This research is a step in filling these missing areas.

CHAPTER 3

SPATIAL LAYOUT EVALUATION METHODOLOGY

3.1. Overview

As mentioned earlier, huge portions of the research on spatial layout evaluation has been based on topological and geometrical architecture of space without considering occupant data of any kind. The current research aims to fill this gap by outlining a methodology and introducing an accompanying framework for evaluation of spatial layouts based on observations of occupant movements. This chapter first describes the Spatial Layout Evaluation Methodology and afterwards presents the Trajectory Data Processing Framework (TDPF).

3.2. Spatial Layout Evaluation Methodology

Quantitative evaluation of spatial layouts based on occupant movement is a four step process (Figure 4. Spatial Layout Evaluation Methodology):

1- Data acquisition: Occupant movements are monitored (manual and/or automated) and recorded as trajectories.
2- Trajectory analysis: Location-based, trajectory-based and time-based analysis of trajectory data is carried out providing objective, quantitative data (trajectories) on occupant utilization of space.
3- Behavior interpretation (identifying appropriate indicators): Observed occupant behavior and indications of occupant behavior from trajectories are matched with layout problems identified within TDPF.
4- Performance Evaluation (aggregating performance values): Based on aggregate performance indicators (yet to be developed) layouts can be evaluated.

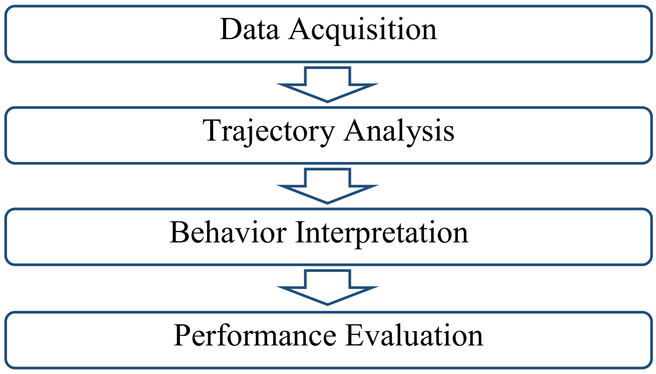


Figure 4. Spatial Layout Evaluation Methodology

The current study mainly focuses on the second step of the layout evaluation process. A framework for carrying out trajectory analysis is developed. This framework provides the necessary infrastructure for spatial and temporal analysis of occupant movements. It includes query tools that can directly be used for developing performance indicators. Moreover, the framework defines an input format specification for trajectory data. The format is valid whether data acquisition is manual or automated. Thus, it can be said that the framework is bridging the first three steps; *data acquisition, trajectory analysis,* and *behavior interpretation*. Step four, *performance evaluation*, is structured upon the first three steps to yield performance evaluation results for spatial layouts.

3.2.1. Data Acquisition

Focusing on architectural design of space and its utilization by the occupant requires the ability to detect occupant behavior, and proficiency in managing spatial quality in terms of occupant satisfaction. Spatial layout evaluation methodology starts with monitoring of occupant movements. Therefore, inhabitants should be at the core of layout evaluation. The main goal in this step is to follow inhabitants and trace their movements in space and time in the form of *trajectories*.

Monitoring occupant behavior is a complex task. It requires a clearly constructed framework to collect useful and accurate data.

3.2.1.1. Occupants

When visually tracking space use, the main objects of tracking are occupants. Defining the occupant is important for understanding what aspects should be observed within the layout. Determining the way occupants are represented is crucial.

Here, occupants are considered as the source for data. This study considers occupants as simple entities that are moving at various directions with various speed. Occupant movements are indicative of a few key aspects of performance in architectural design. These aspects are monitored and are continuously being defined within this framework. Therefore aspects of movement of occupants are limited. For example, movement such as head and/or body rotation is not considered. As occupant modeling complexity increases with future research it will be possible to make more accurate inferences with regard to occupants' relationship with space.

Consequently, occupants are recorded as dots at their centers and turn into trajectories as they move in space. These dots are defined in terms of trajectories. Data collection is done by tracking occupants in the form of trajectories recorded on two-dimensional (2D) plan layouts. Trajectory data is recorded in a format that includes location and time. Occupant trajectories are then preprocessed either as *cell-based* or *vector-based* data. Differentiation of movement data in z-axis is left out of scope.

3.2.1.2. Trajectory Data Acquisition

An objective way to acquire occupant data is capturing and analyzing real-time space utilization information through occupant detection. While there are many areas where such objective data on space utilization can be useful, there are limitations as well. For example, video surveillance is not appropriate for many spaces. However, data obtained through video based tracking also have the potential to complement other emerging technologies such as pedestrian simulations to provide design support. Therefore, the core focus for data acquisition for spatial layout evaluation methodology purposes is to obtain the traces of occupants in the form of trajectories.

3.2.1.3. Manual Tracking

As previously defined in chapter one, a spatial trajectory is a trace consisting of points recorded in terms of coordinate sets and timestamp e.g. $p= (x, y, t)$ (Zheng, 2015) Trajectory analysis has been limited to two dimensions within the scope of this research. However, the proposed methodology and framework already includes the z-dimension in its data definitions for use by future efforts. The *Occupant Layout Interaction Analysis (OLIA)* tool which is a proof-of-concept implementation of the framework also implements the z-dimension in point coordinate definitions e.g. *p= (x, y,* *z, t)*. Within the boundaries of this research, the trajectory data is acquired either manually, through video tracking. Other methods involving computer vision tools or conversion of sensor data into occupant trajectory data have not been employed for focusing primarily on data analysis rather than improving data acquisition methods. Advantages of manual tracking has been that data collection could be much efficient time-wise and it has been possible to track occupants at various instances since it did not require setup as opposed to how it would be otherwise with cameras or sensors. However, data acquisition will definitely be much more precise with movement capturing technologies. Also, data entry would be much easier and much less time consuming had the data acquisition step were automated. As indicated earlier, the focus of the methodology and the framework gravitated more on bridging the gap between the captured occupant data, its analysis in terms of spatial layout evaluation and behavior interpretations. Therefore, acquired data was analyzed and used as a basis for a framework to inquire behavior of occupants.

3.2.2. Trajectory Analysis

Analysis of trajectory data is the second step in Spatial Layout Evaluation Methodology and is the main focus of the current research. The Trajectory Data Analysis Framework is developed in order to provide the necessary infrastructure for spatial and temporal investigations of occupant movements.

Raw trajectory data captured in the first step needs to be analyzed and aggregated in order to better understand the movement patterns which are direct results of spatial layouts. In the first step, occupant trajectories are recorded adhering to a specific file format that is detailed in the next chapter. These trajectory files are first preprocessed and prepared for *cell-based* and/or *vector-based* querying. The processing environments of trajectory data are either *cell-based data processing environment* or *vector-based data processing environment.* Cell-based format lays a grid for processing trajectory data. The grid defines a *resolution* that can be set by the users of the *spatial layout evaluation methodology* tools. Cells within the grid can provide preset locations for analysis. For example, cells may record the number of occupants that visit it. On the other hand, in *vector-based environments,* each trajectory is a spline independent of a grid. Location information is processed by querying the spline directly. The framework requires both environments to be supported. Raw trajectory data can be converted from one format to another. Examples of cell-based and vector-based data processing environments are both given in the next chapter within cases that the spatial layout evaluation methodology is applied.

A set of Criteria, Units and Threshold values are also defined. Based on criteria some basic operations are assigned. Criteria include but not limited to density, angles, proximity of user to closest edge, intersecting trajectory lines, angles of deviation and number of loops. Units are defined to quantify criteria, and their threshold values are set to help users evaluate data as will be explained later. This set therefore creates the possibility of comparatively evaluating spatial layouts based on analysis results.

3.2.3. Behavior Interpretation

Spatial Layout Methodology clearly separates numeric analysis from behavioral interpretation due to the complex nature of movement data. It is not easy to reason *why* someone moved in a particular way by only analyzing *how* the move happened. Not all deviations from the ideal or expected path are related to problems with the layout. Occupants might go off their path or spend more time than expected in a given spot because they are enjoying the space and experience. In Ong et al.'s work, attention is drawn to a *peculiarity* of movement data. This peculiarity is due to the fact that movement data's complexity is related to the *role of context* beyond the two main aspects of trajectories; space and time (Ong et al., 2010). The context has a strong influence on the data. Attaching semantics to trajectory data is of course necessary in order to arrive at an evaluation of spatial layouts. Similarly, priority should be given to understanding how trajectory data should be processed to later serve to understand corresponding spatial meaning. Therefore, a framework is structured for organization of data.

Within the context of the spatial layout evaluation methodology, *occupant behavior* is analyzed by separating *behavior observation* and *behavior interpretation*. (Table 3) Observed behavior is described based on both its *indication in trajectory data* and the *observed occupant behavior*. An *indication in trajectory data* is a reflection of actual occupant behavior on trajectories. Occupant behavior indications are signs that are seen on trajectories that are assumed as reflections of the corresponding observed occupant behavior. Observed occupant behavior is an actual behavior that possibly signals a layout problem.

Interpretation of behavior on the other hand is explained under the title *possible influencing factors* for the observed occupant behavior. Possible influencing factors are separated into two: Influencing factors related to spatial layout problems and influencing factors related to other reasons. There is little available information and explicit knowledge base concerning underlying reasons for observed occupant behavior of occupants. There is a gap in identifying and understanding behavior and correlating them with layout if there are. This gap is the main motivation for this framework that provides the necessary infrastructure for objective analysis of occupant movement observations.

It is not the intent of this research to use observations on occupant behavior as proof for layout problems but merely to provide the necessary analysis tools for other researchers to further the researchers' understanding of architectural layout evaluation.

Yet, identifying a set of architectural layout problems that could be discovered through observation of occupant movements was the first step of this research. Below is the list of identified layout problems:

- Over-crowded Space
- Wasted Space
- Clutter, indirect access
- Insufficient clearance
- Bottlenecks
- No alternative / better passage assigned
- Inefficient Way-finding
- Unpredictable Usage
- Inflexibility

Among this extendable list of identified layout problems, the first seven problems were picked to form the scope for the research. This set allowed testing of the framework capabilities in handling all three types of queries that were identified, namely, location-based, trajectory-based and time-based queries. The layout problems are discussed below.

3.2.3.4. Over-crowded Space

Looking at how spaces are used, one of the major concerns is that some zones are un-proportionately more crowded than others within a certain space. Thus those zones are used by more people than others. However, at certain times of the day *over-crowdedness of space* can be a layout problem that can only be fixed if it can be defined and/or measured. Therefore, this problem can be defined in terms of *density*. *Density* is interpreted as *number of people* per specified area. Depending on different evaluation cri-

Table 3. Interpretation of Occupant Behavior.

	Behavior Observation			**Behavior Interpretation**	
				Possible Influencing Factors	
	Indication in Trajectory Data	***Observed Occupant Behavior***		**Layout Problem**	***Other***
Within Scope	*Too many steps compared to other zones*	*Accumulating at a certain zone*	⟺	Inadequate space dimensions/Over-crowded Space	*Attractors etc.*
	No step counts compared to other zones	*Avoiding certain zones*	⟺	Wasted Space	*Repellants: low or no balustrades. Insecure details*
	Changing direction with sharp angles in trajectories	*Interrupted Navigation*	⟺	Clutter, indirect access	*Obstacles*
	Changing pace during navigation		⟺	Insufficient clearance	*Intentional delays; Stopping by etc.*
	Overlapping routes(trajectories)	*Bumping into each other within an adequate space*	⟺	Bottlenecks	*Waiting for each other*
	No stops or deviation in Smooth trajectory lines or Curves within the observed layout	*Transiting*	⟺	No alternative / better passage assigned	*Not Specified*
	Inconsistent trajectory, loops, backtracking etc.	*Wandering as if looking for something rather than heading towards an end*	⟺	Inefficient Wayfinding	*Not Specified*
	Unexpected crowd in certain zones	*Unintended usage*	⟺	Unpredictable Usage	*No assigned space for certain functions/needs*
	Changes in routes due to new layout organizations	*Occupants wanting to change furnishing layout frequently*	⟺	Inflexibility	*Not Specified*
	Either no step counts or too many compared to other zones	*Uncomfortable and/or cannot focus*	⟺	Not Specified	*Noise*
	–	*Unease; Sweating, or cold, or too bright or too dark*	⟺	Not Specified	*Physical Inconvenience*

teria, the specified area and the desired density will vary.

3.2.3.5. Wasted Space

The same concern with inadequate space dimensions can be valid in case of space that is never being used. *Wasted space* in space planning literature has earlier been defined as "…Wasted space is calculated as the area of the building boundary minus the total area used as living space." (Michalek, et al, 2002) Therefore, no sign of occupancy can be an indication of *wasted space* unless that zone serves another purpose that is not visible in the plan layout. The existence of wasted space can also be investigated in terms of *density* within the framework.

3.2.3.6. Clutter, Indirect Access

Clutter, indirect access alongside various obstacles or intentional delays and/or stopping by etc. on layouts is considered to be a possible reason for interrupted navigation. Implications of *interrupted navigation* on trajectories are either *changing direction with sharp angles in trajectories, or changing of pace.* This problem can be evaluated based on analyzing angular changes in trajectories. Interpretation of data can be done by investigating the angles and setting threshold values. For example, a simple analysis should reveal trajectories with deviations higher than 30˚. Naturally, threshold values are expected to change according to user input and preferences.

3.2.3.7. Insufficient Clearance

Navigation is interpreted as occupant's ability to move through a certain space. This ability depends on references that occupants get from their own virtual map of that place. Thus the occupant has targets and forms certain routes in their minds when they enter a space. Interruption of this is a feature that displays discrepancy among intended routes (in the designed layout) and occupant's navigation preferences.

When space does not allow the occupant to navigate in smooth trajectories interrupted navigation comes into play as a layout problem. An indication of this problem can be hard angles in trajectories and the influencing factors can be traced from *proximity to closest edges* or *changing pace during navigation.*

3.2.3.8. Bottlenecks

Spatial layout design dictates routes for inhabitants. Within these routes constrictions occur depending on use of space. Actual occupant behavior instances of *bumping into each other within an adequate space* points to *bottlenecks*. Bottlenecks are seen and interpreted as *overlapping routes* (trajectories) and evaluated based on *frequency per hour*.

3.2.3.9. No Alternative / Better Passage Assigned

When layout design falls short of controlling each point in evaluated space, layout problems may occur. Problems arise at instances when place is only passed through. *No stops or deviations in smooth trajectory lines or curves within the observed layout* would be the indication of a possible layout problem. Thus the actual occupant behavior appears as *transiting.*

No alternative / better passage assigned is the statement for defining the layout problem for this case. It is observed that transiting through space happens at instances when there are no other means of circulation possible to an adjacent space. Therefore, if angles of deviation on trajectory lines are smaller than 20˚ (tentative) it is assumed that it is a transiting behavior. This behavior signals the possibility of absence of a passage for occupant who do not need to go through or stay in this place.

3.2.3.10. Inefficient Wayfinding

Wayfinding can be intuitive or inefficient. Architectural design is mostly responsible for wayfinding convenience in spaces. Appropriate layout design could provide intuitive wayfinding for occupants. Inefficiency in wayfinding may and is solved during post-occupancy by inserting signage into space. However, installing signage is not a sufficient solution for fixing *inefficient wayfinding* in spaces. When inefficient wayfinding is the case, occupants are observed with a typical behavior; *wandering as if looking for something rather than heading towards an end.* Thus the i*ndication in trajectory data* would involve the detection of *inconsistent trajectory, loops, backtracking* etc. by the tools provided by the framework.

3.2.3.11. Unpredictable Usage

A feature of space that appears when the architect has intended a specific use for a certain area and the space is used in a different way. Architectural design process starts with the program or a design brief that defines the design problem. The designer employs his/her tacit knowledge in order to take certain design decisions. However, those design decisions do not seem to be determinant of the outcome i.e. the performance of spatial layout. On certain occasions, the designed space might be used in completely other ways than assigned by the architect.

Unpredictable usage as a layout problem manifests itself as *unexpected crowd in certain zones* on analyzed layouts and *the actual occupant behavior* is observed as *unintended usage*. Therefore the other possible influencing factors for this layout concern is not limited to *no assigned space for certain functions/needs* and is open for additions.

Unpredictable usage is left out of the scope of this dissertation.

3.2.3.12. Inflexibility

When space does not allow for customization for the occupant, it may lower spatial quality. Space should be designed adequately to suit design needs. Architectural design practice intuitively suggests that it is done to conform to minimum requirements of current needs of occupants. However, in an era of accelerated pace of change, space needs change much more frequently than that of earlier decades. Therefore, flexibility becomes a crucial quality of space.

Flexibility as a feature of spatial quality is being explored in several domains. A rare research on flexibility in space layouts provides a first step towards empirically illustrating in detail how the organizational flexibility needs to be analyzed. Open office is an outcome of the urge to find flexibility in office layouts. Relating organizational behavior with spatial quality in terms of flexibility, the author illustrates the merits of taking spatial design of workspaces into consideration when evaluating organizational behavior. Therefore, it suggests that all implementations facilitating flexibility needs to be considered thoroughly taking both ends into consideration. (Varlander, 2012)

3.2.3.13. Other Possible Influencing Factors

Approaching the problem space through specific layout problems does not disclose the analytical sequence needed for this research. Therefore an alternative relational table based on occupant trajectories does help lay a groundwork. Other possible influencing factors are either uncountable interpretation entities or non-negligible influencing factors that negate the possibility of a layout problem as the cause of a certain actual behavior.

3.2.4. Performance Evaluation

Upon the interpretation of behavior based on analysis of trajectory data, the final stage where evaluation and assessment of the layout follows. However, as stated earlier a framework is needed to construct an evaluation system. For such a construction, criteria are needed and for a quantitative evaluation, units and operations representing the set criteria are needed. (Table 4) Finally, huge quantities and points are required for a future goal of obtaining Layout Evaluation Scores (LES).

The setup of TDPF, suggests the construction of an efficient system to identify a *context-based port* accepting location, resolution, time and criteria input, *a process base* for running algorithms based on necessary operations to run on trajectories and *an output port* for revealing values to serve as a basis for Layout Evaluation Score (LES) Therefore, LES being the final result to come out from this framework.

As explained previously, *Indication in trajectory data* that is based on behavior observation displays indications such as *too many steps compared to other zones*, *accumulating at a certain zone*, *inadequate space dimensions/over-crowded space*, *attractors* etc. are then corresponded to the *possible layout problems* list. Therefore, the criteria for that specific layout problem, in this case *density*, the units for counting occupants per a specified area per time such as *No. of Occupant/m2/min*, and threshold values such as >*X occupants* are the quantifiers of this evaluation process. Corresponding LES point in *a points out of n* format is assigned to the layout that is being evaluated. When added up for all layout problems they display a total value for LES. Currently, threshold values are set by users of TDPF. However, through accumulation of data, the framework is expected to reach and hold statistically reliable values. Therefore, a future work will be the formation of a "Layout Performance Index" that could be driven from accumulation of LES values for architectural layout evaluations.

Table 4. Layout Evaluation Table

	Behavior Observation			Evaluation			
				Assessment			
	Indication in Trajectory Data	**Possible Layout Problem**		**Criteria**	**Units**	**Threshold Values**	**Corresponding LES Points**
Within Scope	*Too many steps compared to other zones*	Inadequate space dimensions/Over-crowded Space	⟺	Density;	No. of User / m^2 / min	>X users	a points out of n
	No step counts compared to other zones	Wasted Space	⟺	Density;	No. of User / m^2 / min	<X users	b points out of n
	Changing direction with sharp angles in trajectories	Clutter, indirect access	⟺	Angles	Degree	>X degrees on trajectory lines	c points out of n
	Changing pace during navigation	Insufficient clearance	⟺	Proximity of user to closest edges	cm	<X cm during navigation	d points out of n
	Overlapping routes(trajectories)	Bottlenecks	⟺	Intersecting trajectory lines	times / hour	> times/hour	e points out of n
	No stops or deviation in Smooth trajectory lines or Curves within the observed layout	No alternative / better passage assigned	⟺	Angles of deviation	Degree	< X°	f points out of n
	Inconsistent trajectory, loops, backtracking etc.	Inefficient Wayfinding	⟺	Number of loops	times / route / Frequency	X	g points out of n
	Unexpected crowd in certain zones	Unpredictable Usage	⟺	_	_	_	h points out of n
	Either no step counts or too many compared to other zones	Not Specified	⟺	_	_	_	j points out of n
	_	Not Specified	⟺	_	_	_	k points out of n

CHAPTER 4

TRAJECTORY DATA PROCESSING FRAMEWORK

4.1. Overview

The background literature summarized in the second chapter, is mainly focused on evaluating layouts utilizing criteria based on topological relationships and geometry. Occupant interaction with architectural spaces is mostly overlooked. The current research is focused on establishing a platform for making use of occupant movement data for spatial layout evaluations. To this end, in this thesis, the Spatial Layout Evaluation Methodology has been defined and an accompanying operational framework has been developed. This chapter describes this framework named Trajectory Data Processing Framework (TDPF)

4.2. Trajectory Data Processing Framework

Trajectory Data Processing Framework facilitates semantic translation of raw occupant movement data acquired through observation, to quantified performance parameters through queries and calculations. The framework is set up for defining algorithms based on operations that can be run on trajectories to provide quantitative analysis tools for researchers to support their *behavior interpretation* and later layout *evaluation* processes. The framework is structured to support the analysis phase of the methodology but also defines how data will be organized in the observation stage and provides the necessary reports that will be used in the interpretation stage, bridging the first three stages of the methodology.

4.2.1. Trajectory Data Analysis File

A TDF is a simple excel file. It uses the *csv* and/or xlsx format. This Excel file has designated ranges that hold trajectory ID numbers that correspond to coordinates. Next column has timestamps. For each trajectory, two equal length lists, one for coordinates and the other for timestamps are recorded. Table 5 displays the data entry format of TDF.

Table 5. TDF Trajectory Data Analysis File

Layout Name:		*YU Cafe Ground*					
Operation:		*Create Trajectory*					
Points							
Trajectory ID #		**1**		**2**		**3**	
		Coordinates	**Time**	**Coordinates**	**Time**	**Co**	**T**
		{49.2, 32.8, 0.0}	00:00:07	{x,y, z}	t		
		{49.7, 31.9, 0.0}	00:00:12	{x,y, z}	t		
		{50.2, 31.0, 0.0}	00:00:18	{x,y, z}	t		
		{50.8, 30.2, 0.0}	00:00:28	{x,y, z}	t		
		{51.4, 29.5, 0.0}	00:00:45	{x,y, z}	t		
		{52.1, 28.7, 0.0}	00:00:59	{x,y, z}	t		
		{52.8, 28.0, 0.0}	00:01:17	{x,y, z}	t		
		{53.6, 27.3, 0.0}	00:01:49	{x,y, z}	t		
		{54.3, 26.7, 0.0}	00:02:07	{x,y, z}	t		
		{55.1, 26.0, 0.0}	00:02:16	{x,y, z}	t		
		{55.8, 25.4, 0.0}	00:02:26	{x,y, z}	t		
		{56.6, 24.7, 0.0}	00:02:43	{x,y, z}	t		
		{57.3, 24.0, 0.0}	00:02:59	{x,y, z}	t		
		{58.0, 23.3, 0.0}	00:03:22	{x,y, z}	t		
		{58.7, 22.6, 0.0}	00:03:45	{x,y, z}	t		

4.2.2. Processing Trajectories

A list of operations and tools on trajectories (Table 6) is derived from occupant behavior indicators on trajectories that are pointing out to possible influencing factors as explained in chapter three. This list is expected to expand with evaluation criteria and from how they could be interpreted and evaluated in mathematical terms. While the indications in trajectory data are considered to point out to certain layout problems, the research requires analytical tools and operations to compute magnitudes and operate on trajectories.

Table 6. List of operations and tools on Trajectories in TDPF.

Operations on trajectory		Indication in Trajectory Data	Examples of Queries/Use
1	Create trajectory	n/a	How do occupants navigate the layout in concern
2	Number of trajectories	Too many trajectories through a zone compared to others No trajectories going through a zone	How many trajectories are there similar (full or partial juxtaposition) to Trj. # X?
3	Points of Inflection	Changing of direction	Where do sharp changes in trajectories take place?
4	Closest proximity	Insufficient clearance	When do occupants slow down during navigation?
5	Angle of deviation	Changing direction with sharp angles	Do occupants transit through the space
6	Intersecting trajectory lines	Unexpected crowd in certain zones	Where are the bottlenecks?
7	Average of trajectories	n/a	Where is the busiest zone?
8	Definition of loop	Forming closed or open loops during navigation	Are there instances of backtracking and/or wandering around?
9	Number of loops	Looping trajectories	How many instances of backtracking and/or wandering around are there?
10	Number of occupants	n/a	How many occupants navigate the layout in concern
11	Checking control points	Too many trajectories through a zone compared to others /No trajectories going through a zone	What if trajectories change?
12	Time data entry	Changing pace during navigation	When and where is most crowded?
13	Speed	Changing pace during navigation	When do occupants slow down?

4.2.2.1. Query Classification

Possible queries that can be directed have been analyzed as a first step for developing the TDPF. Table 8 lists some of the various queries that are supported by the TDPF. Queries are classified in terms of how they process trajectory data (operations) and what they produce as a result (output). The output data can be counts, coordinates, zones, time intervals, and booleans.

The results of the analysis established a query classification where three types of queries exist:

1. Location-based
2. Trajectory-based
3. Time-based

Queries for spatial layout analysis contain and require more than a single type of data. Some applicable queries are identified and classified based on computation types.

While one query requires a *Location-based* analysis, a sub-query may involve *a trajectory-based* analysis. While a *Location-based* analysis involves queries concerning *zones, movement, area*, and *direction* data, an analysis type *based on time* may involve *speed* in computation processes. Whereas speed and area may be irrelevant for another type of inquiry based on *time*. In order to support all queries, raw trajectory data is required to have a temporal component in the form of timestamps that accompany coordinate data.

Table 7. Query Types for Layout Analysis

Analysis Type	Queries concerning;				
	Zones	Speed	Movement	Direction	Area
Location- based Computation	✓	-	✓	✓	✓
Trajectory- based Computation	✓	-	✓	✓	-
Time- based Computation	✓	✓	✓	✓	✓

Especially for handling queries dealing with location, it is desirable to apply a grid of appropriate size to the spatial layout and utilize *cell-based* data processing. On the other hand, most other queries on trajectories require handling trajectories as splines and utilize *vector-based* processing. Both types of processing are required and are supported by the framework that is developed.

Table 8. Query Classification Based on Input and Output Types

Query Classification

Queries	INPUT	PROCESS	OUTPUT
Subqueries	**Type**	**Operations on trajectory**	**Type**
How many trajectories are there similar (full or partial juxtaposition) to Trj. # X?	Trajectory Based	Checking control points, Number of trajectories	Counts
Where do they meet?	Location Based	Checking control points	Coordinates
How many loops are there in Trj. # X?	Trajectory Based	Definition of loop	Counts
Where do the loops form?	Location Based	Zoning	Zones
How many trajectories are there containing more than X number of loops	Trajectory Based	Number of loops, Number of trajectories	Counts
Where do the angles of deviation go above X^0?	Trajectory Based	Angle of deviation and/or Point of Inflection	Coordinates
Where is the densest zone (> 2 people/ m2)?	Location Based	Intersecting trajectory lines, Number of Occupants	Zones
Are there smooth trajectory lines with angle deviation <x	Trajectory Based	Angle of deviation	Boolean
Where do those lines appear?	Trajectory Based	Angle of deviation	Coordinates
Are there smooth trajectory lines with no stops	Trajectory Based	Angle of deviation	Boolean
How many times do occupants come closer than X cm to an obstacle during navigation?	Trajectory Based	Closest proximity (option: See people as obstacles)	Counts
Where do occupants come closer than X cm to an obstacle during navigation?	Location Based	Closest proximity (option: See people as obstacles)	Zones
When do occupants slow down during navigation?	Time Based	Number of loops, Closest proximity, Angle of Deviation	Time Intervals

4.2.2.2. Criteria

Without criteria it is not possible to run quantitative analysis. Qualitative data is transformed into qualitative transcription with the help of criteria definitions and decisions. *Density, Angles, Proximity of user to closest edges, Intersecting trajectory lines, Angles of deviation, Number of loops* are all examples of this transcription. Therefore, criteria in this system have evolved into operations that eventually yield evaluation scores.

4.2.2.3. Units

Set of operations used in the framework require units. The units used in TDPF are *Number of Users /area /time (optional)* for defining *density*, *distance* for *proximity*, *degrees* for *deviation*, *frequency* for *intersecting trajectory lines* and/or *number of loops*. Units are considered as means of evaluation.

4.2.2.4. Threshold Values

Threshold values used in this research will be set by the user of OLIA through a future user interface as shown earlier in Table 4. Users are expected to reach optimal values to set for criteria after several iterations. In future work, it is a possibility to keep track of threshold values set by the users and reevaluate their efficiency within OLIA. This may lead to a set of standard values for the set of criteria.

Setting standards for threshold values in the framework is left out of scope of this dissertation. This has obvious reasons. First, it requires the framework to be fully set through extensive additional research. Second, there needs to be huge amounts of data processed to reach valid values that can be used in standardization of knowledge.

4.3. Implementation – OLIA

4.3.1. The OLIA Plugin for Rhinoceros/Grasshopper

An operational implementation of the Spatial Layout Evaluation Methodology is developed as a plugin for the visual programming environment Grasshopper. The plugin is called OLIA, an acronym for Occupant Layout Interaction Analysis (OLIA). It is designed to work in Rhino/Grasshopper environment. It handles all data related to spatial layouts to be evaluated. It is envisioned as a toolkit that includes all input, processing and output tools for layout evaluation. Although *Excel* acts as a great tool for data storage, processing and analysis, it does not serve as efficiently as a graphical programming tool when it comes to visualization of other operations within OLIA and TDPF. An example of this may be analyzing loops. Loops need to be geometrically defined and detected. Although this can be done in *Excel*, it requires much refined data entry and is labor intensive. As mentioned earlier, this led the researchers to a visual programming tool called *Grasshopper* that works within *Rhino* 3D modeling software. OLIA is a plugin that works on this platform and still works with *Excel* for various phases within TDPF.

OLIA allows users to run necessary operations on trajectories. It receives data from list sources such as Excel sheets. Trajectory data files import and export data through a cloud service called that bridges data between MS Excel and Rhino/Grasshopper interface. This transfer may as well be done independently between the two platforms however, there is a shift in information based applications towards cloud based storage and operations enabling collaborative practices. Therefore this cloud-based exchange will not be limited to certain software and will expand data sharing practices across many platforms.

While Excel files hold trajectory data as coordinates and timestamps, the spatial layout is imported to or prepared in vector-based environment. All representation of layout information in this environment including walls and furniture is drawn using *curves/NURBS. NURBS* allow the occupant layer represented in trajectory splines to communicate with the fixed layout elements during analysis.

Through this plugin, users can analyze trajectories formed by occupant navigation and evaluate their plan layouts. For the current state of OLIA package it is only possible to work within Rhino/Grasshopper interface (Figure 5).

There are two possible user types of OLIA:

- Visual Programming literate researchers/architects
- Programming illiterate researchers, architects, builders, facility managers etc.

OLIA plugin will enable the first type of users with a set of tools and operations that they can manipulate. For the second type of user, the draft to illustrate a possible user interface (Figure 6) is designed to display the type of interaction that will be available to the user.

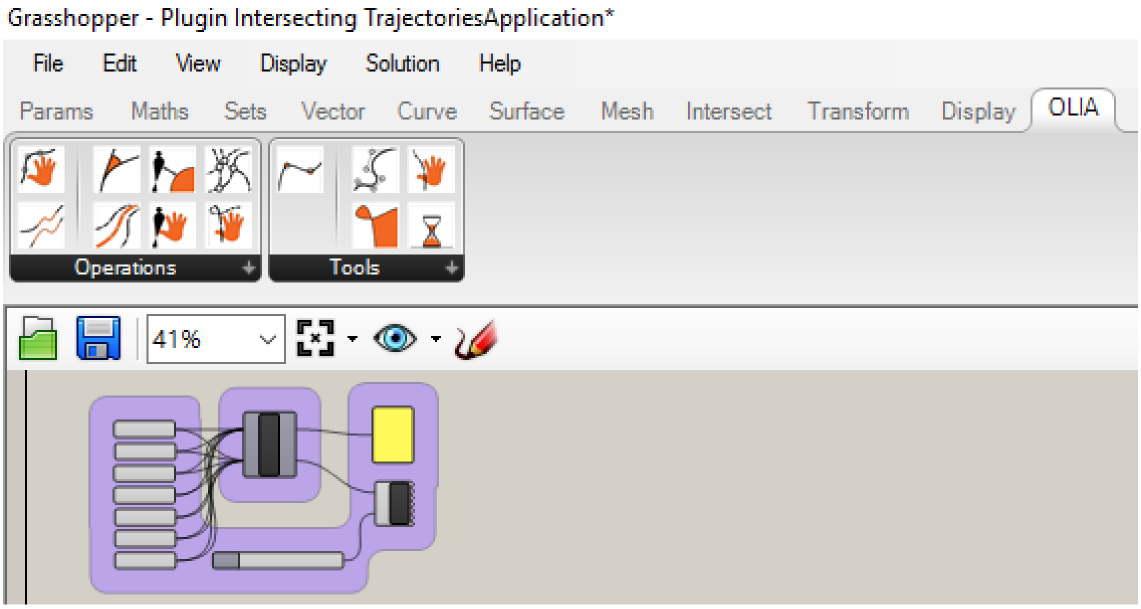


Figure 5. OLIA plugin user interface on Rhino/Grasshopper

This general user interface (GUI) is left out of scope of this thesis and is not developed further. The content of this interface is explained along with Trajectory Data Processing Framework (TDPF). The spatial layout evaluation methodology provides the user with a range of analysis options. Therefore, the evaluation step is at its infancy and needs TDPF to establish a semantic platform for spatial layout evaluation practices. However, OLIA is a tool that is already operational for the first type of user who can set their own interpretation and evaluation values for their practices.

To help process graphic information on trajectories into quantitative data 3D modelling software environment called Rhinoceros is used to build up a plugin set in Grasshopper, an editing software for graphical algorithms. Next subchapter explains in detail, the current but not limited list of operations and tools utilized in this spatial layout evaluation methodology.

4.3.2. OLIA Tools and Operations

Tools and operations in OLIA comprise a set of basic analytical operations that create, modify, edit and analyze trajectories.

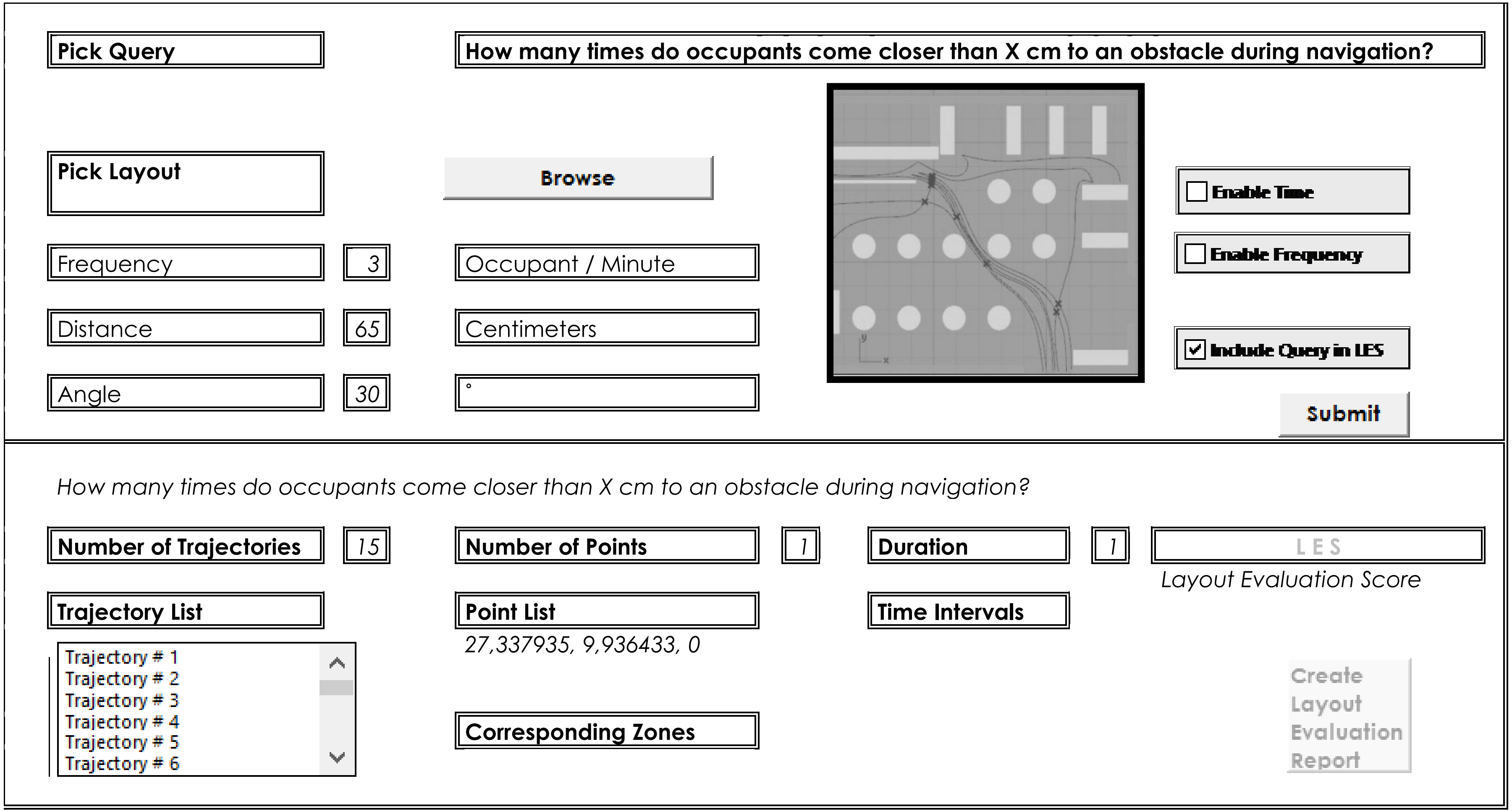


Figure 6. A Future Illustrative General User Interface (GUI) Draft for second type of OLIA users

Table 9. Tool and Operation Clusters of OLIA in Rhino/ GH

Tool and Operation Clusters in OLIA				
		Operation	Tool	GrassHopper Definitions Used
1	Create trajectory		✓	
2	Number of trajectories	✓		List Length + End Points+ Point List
3	Points of Inflection		✓	InflectionSolver + List Item+ Deconstruct
4	Closest proximity	✓		Curve Proximity + Delete Consecutive
5	Angle of deviation		✓	CurveIntersection + Evaluate + Angle
6	Intersecting trajectory lines	✓		Multiple Curves + List Item + Deconstruct
7	Average of trajectories	✓		Divide + List + Line + Nurbs
8	Definition of loop		✓	Curve SelfIntersect (Option)+ List Item
9	Number of loops	✓		Curve+ Curve Self (CX)+Delete Consecutive+List Length+Length
10	Number of occupants	✓		Rectangular grid + Curve Intersection+Path Mapper+ListLength
11	Checking control points		✓	Control Points+Point+VectorXYZ+Move+Nurbs Curve+Curve
12	Time data entry	✓		Interpolate+Curve+Divide Distance+Time+Deconstruct Date+Construct Smooth Time
13	Speed		✓	Time+VB Script Multispan+ VB Script FormatSpan

These tools and operations are explained individually below:

4.3.2.1. Create Trajectory 

Trajectory data is stored in the form of coordinates and time corresponding to those point coordinates. This type of data can be analyzed either with temporal information or solely by its geometry. Therefore, OLIA supports both types of trajectory data - with time and without time. With the use of the tool, *Create Trajectory* (Figure 7), the user can import point lists into this software environment and utilize the plugin package on recreated trajectories.

Trajectory data to be imported can either be lists of points extracted at certain length intervals such as *points/100cm* or at time intervals such as *points/20sec.* Once the trajectories are created, users can make modifications and add alternative trajectories for analytical purposes. Therefore, OLIA leaves space for the user to experiment on spatial use data.

Independent from however it is imported the trajectory data is displayed as vector-based layout graphic information within the environment (Rhino) that OLIA operates on. Therefore, the user of the toolkit can visually track and control the analysis process at their own pace pertaining to their own analytical purposes. Trajectories, once created in this environment, can be listed as points or vectors or corresponding cells depending on user preferences.

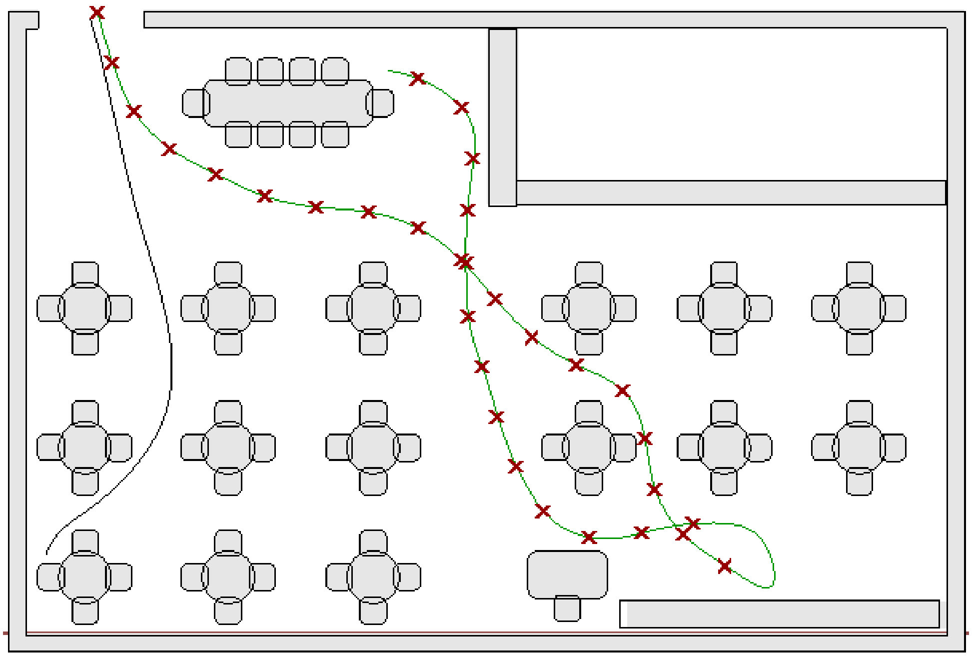


Figure 7. Sample layout displaying OLIA tool "Create Trajectory" with points at 100 cm intervals

Name:	*Create Trajectory*
Description:	*To enable the user with a tool to bring trajectory data into the analysis environment of OLIA*
Precondition:	*User should have acquired trajectory data of occupant navigation from the field of which the spatial layout will be evaluated.*

Flow of Events: - *Have the list containing vertex coordinates of trajectories (.xls or a .csv file.)*

- *Import or copy/paste coordinate data into a panel (Location Entry Panel) onto the Grasshopper Canvas*

- *From OLIA tab on the component palette, pick component called "Create Trajectory" and bring onto the canvas*

- *Connect the vertices list to the Input port named "V"*

- *Create a number slider to connect to the input port named "D" to define intervals at which the trajectory vertices were recorded*

- *Pick an element called "Curve" and bring in*

- *Connect from the output port named "C" to the Curve element*

Postcondition: *Trajectory should have been created*

Start using analysis tools and operations on trajectories created

4.3.2.2. Number of Trajectories 

Number of trajectories represent number of people inhabiting the space that is being analyzed. This operation counts trajectories based on the order that they are created within OLIA environment. Independent of its geometry and identity, each trajectory is counted and therefore listed as the number of occupants. Although number of trajectories represent number of users, the tools ignores real occupant identity and treats each trajectory as a new identity. Therefore, it does not track whether an occupant navigates more than once, forming several trajectories at different times.

Keeping track of the quantity of trajectories allows for several operations. Counting their quantities is one of the basic operations done with trajectories. However, there are constraints when counting trajectories. Trajectories may be counted and/or listed based on temporal information or without any time data involved. Retrieving information on number of trajectories gives the ability to list which trajectories are subject to the list of operations. For example, in the case of an analysis related to *density*, it may be important to count number of trajectories at a certain time interval, while at another research the user may ignore time and only focus on counting totals.

This tool comes with its own tagging function as seen in (Figure 8) that enables the user with the ability to track trajectories according to their numbers.

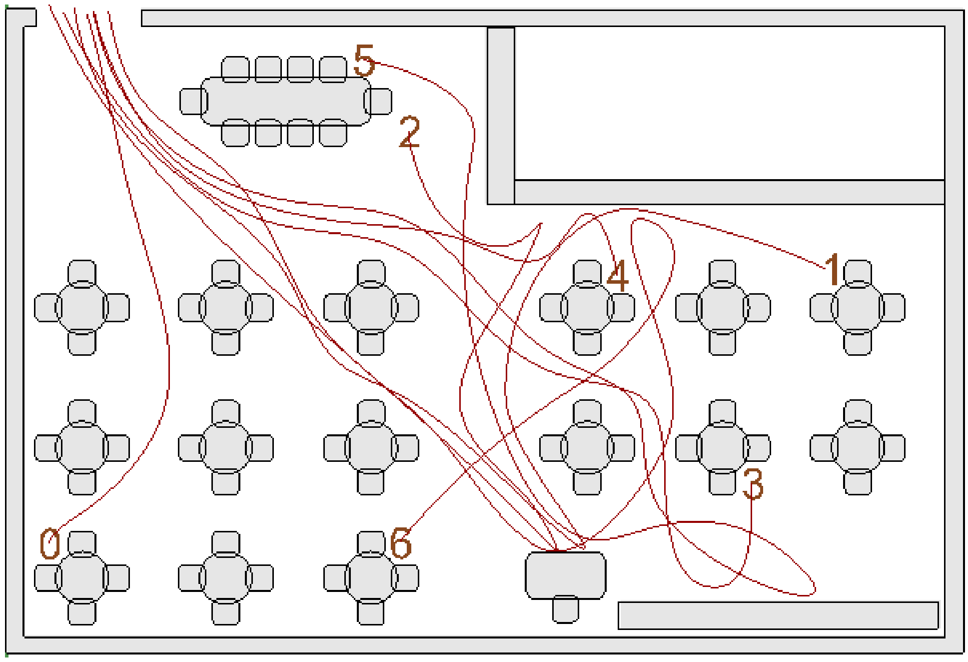


Figure 8. Sample layout displaying OLIA tool “Number of Trajectories”

Name:	*Number of Trajectories*
Description:	*An operation to count and tag trajectories*
Precondition:	*User should have created trajectories within Rhino/Grasshopper environment*
Flow of Events:	*- Have trajectories already created as “Curves”*
	- From OLIA tab on the component palette, pick component called “Number of Trajectories” and bring onto the canvas
	- Connect all trajectory curves to both input ports named “L” and “C”
	- Pick an element called “Panel” and bring onto canvas
	- Connect from the output port named “L” to the Panel element to see the number of trajectories displayed in the panel
	- From “Display” tab on the component palette, pick component called “Point List” and bring onto canvas to tag number of trajectories.
	- Connect from the output port named “E” to the input port named “P” on the Point List element
	- Create a number slider to connect to the input port named “S” on the Point List element to adjust text size
Postcondition:	*Trajectories are counted, listed and tagged at their end points*
	Start using analysis tools and operations on trajectories created

4.3.2.3. Points of Inflection 

Inflection points define the start of a new direction and a new set of properties of sub-curves within splines. While the *points of inflection* tool indicates a directional change in trajectories, it is functional for curve analysis. The point at which concavity of a curve changes is the point of inflection therefore all inflection points on a curve (Figure 9) are listed as coordinates in x, y, z format, can be viewed as points on curves as seen in the sample and can be listed by their indices.

This tool can work with another tool *angle of deviation* to help users view instances of *changing direction with sharp angles in trajectories.* According to TDPF, it might be an indication of interrupted navigation and could be caused by a layout problem such as *clutter or indirect access* in the space that is being analyzed.

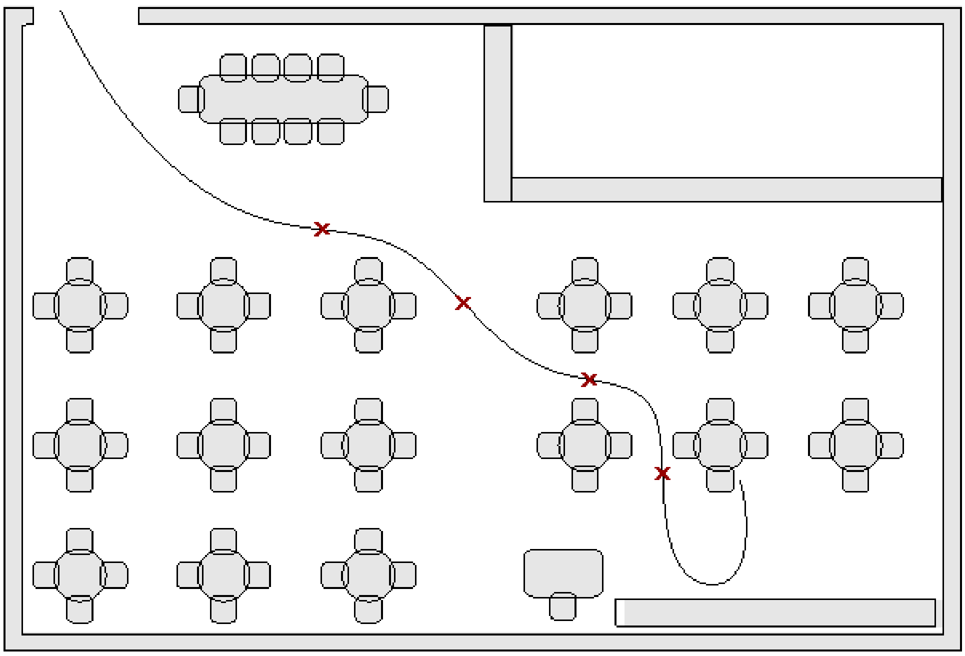


Figure 9. Sample layout displaying OLIA tool "Points of Inflection"

Name: *Points of Inflection*

Description: *A tool to view directional changes in trajectories, for curve analysis purposes*

Precondition: *User should have created trajectories within Rhino/Grasshopper environment*

Flow of Events: - *Have trajectories already created as "Curves"*

- *From OLIA tab on the component palette, pick component called "Points of Inflection" and bring onto canvas*

- Connect the trajectory curve to find inflection points for to input port named "IC"

- Pick an element called "Panel" and bring onto canvas

- Connect from the output ports named "X", "Y" and "Z" to the Panel element to see the coordinates of inflection points

- Create a number slider to connect to the input port named "i" to pick the index of which inflection points to view

Postcondition: *Inflection Points on trajectories are listed*

Coordinates of inflection points are listed

4.3.2.4. Closest Proximity 

This operation works as a tool to compute relations of a trajectory curve with obstacles, with each other, and with zones that are defined by its geometry as shown in Figure 10. It find the shortest distances between curves that are being analyzed, at which points those curves come closest and sorts them.

While using this operation the user has the option to either compute other occupants (trajectories) as obstacles or not. Therefore this operational can lead the user to derive layout analysis results depending on the threshold values that are set by the user. Within TDPF, users can find corresponding behavioral indications such as *changing pace during navigation* to layout problems such as *insufficient clearance*. Therefore, the user can observe alternative and new relations between geometry and semantics.

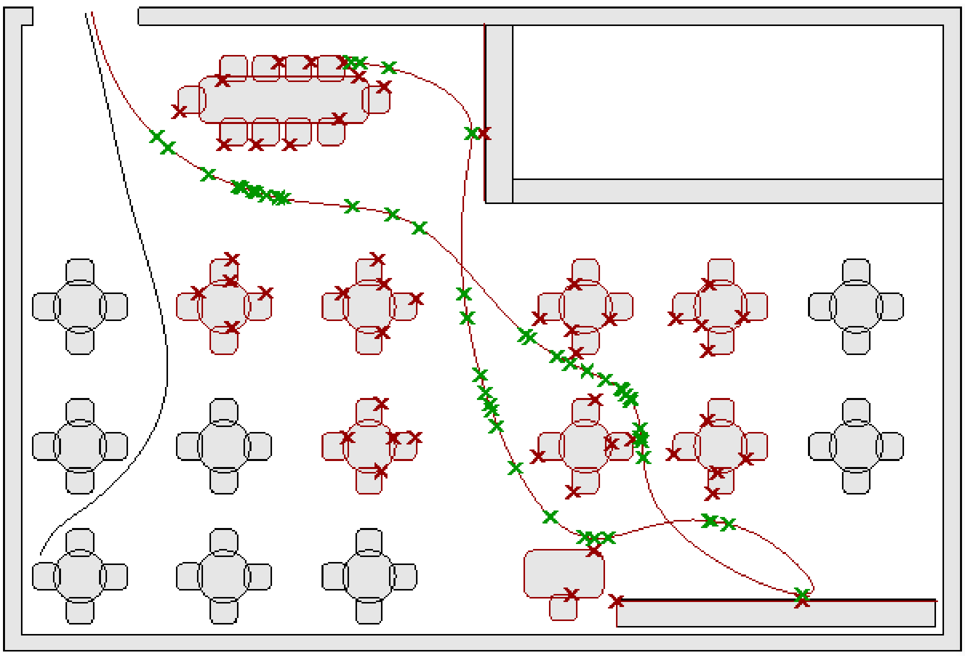


Figure 10. Sample layout displaying OLIA operation "Closest Proximity"

Name: *Closest Proximity*

Description: *An operation to compute distances of a trajectory curve with other geometries ie other trajectories, elements of layouts etc.*

Precondition: - *User should have created trajectories within Rhino/Grasshopper environment*

- *Layout elements should have been defined with curves within Rhino/Grasshopper environment*

Flow of Events: - *Have trajectories and other layout elements already created as "Curves"*

- *From OLIA tab on the component palette, pick component called "Closest Proximity" and bring onto the canvas*

- *Connect each two trajectory curve to corresponding input ports, one named "A" and the other named "B"*

- *Pick an element called "Delete Consecutive (DCon)" and bring onto canvas and triplicate*

- *Connect output port named "A" on "Closest Proximity" component with input port named "S" on "DCon" component*

- *Connect output port named "B" on "Closest Proximity" component with input port named "S" on "DCon" component*

- *Connect output port named "D" on "Closest Proximity" component with input port named "S" on "DCon" component*

- *Pick an element called "Panel" and bring onto canvas and triplicate*

- *Connect from the output port named "S" on each "DCon" component to the "Panel"s for each.*

Postcondition: *The Panel connected from "A" displays the points with closest proximities on curve "A"*

The Panel connected from "B" displays the points with closest proximities on curve "B"

The Panel connected from "D" displays the distances between points with closest proximities on curve "A"

4.3.2.5. Angle of Deviation 

Angle of deviation is a tool for analyzing trajectory curves in terms of angles formed throughout their paths. The tool assigns vectors at certain points on trajectory curves and reveals the angles between them and continuation of the curves (Figure 11). Angle of deviation is a complementary tool for another tool; *points of inflection* in trajectory analysis.

Angles formed throughout the trajectories are considered as indications of possible layout deficiencies for occupant behavior. As mentioned earlier, work on *isovists* (Benedikt, 1979) also looks at paths and reveals that movement is expected to follow a path with least angles. Therefore, users can determine their own range of angles as thresholds for their own analytical purposes while using OLIA.

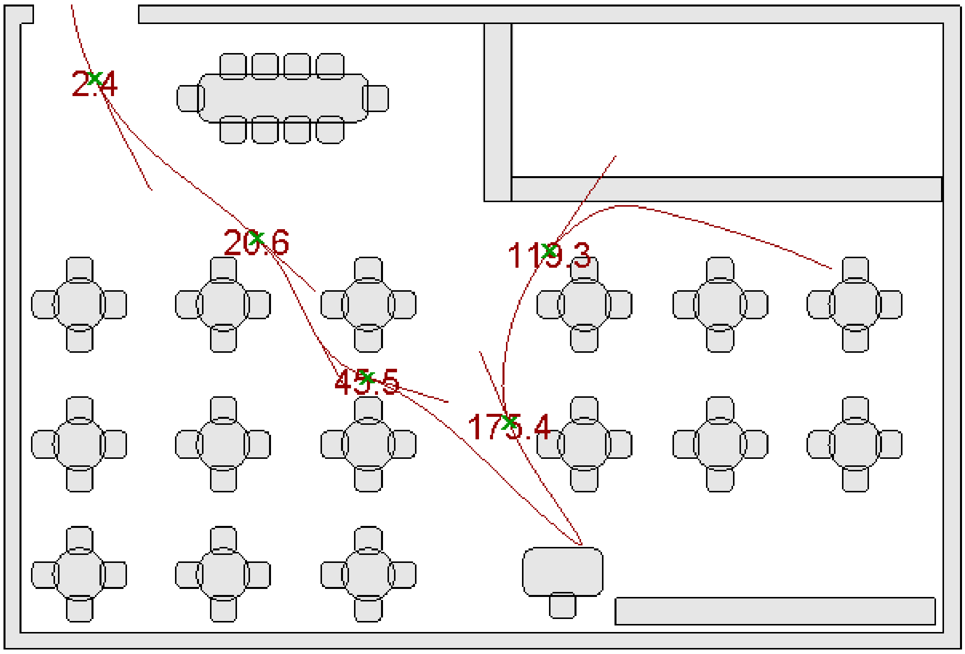


Figure 11. Sample layout displaying OLIA operation "Angle of Deviation"

Name: *Angle of Deviation*

Description: *A tool to assign vectors at user selected points on trajectory curves and reveals the angles between them and continuation of the curves*

Precondition: *User should have created trajectories within Rhino/Grasshopper environment*

Flow of Events:
- *Have trajectories already created as "Curve"s*
- *Create tangent vector as "Curve"s at instances where curves change direction or at "Inflection Points"*
- *From OLIA tab on the component palette, pick component called "Angle of Deviation" and bring onto canvas*
- *Connect each trajectory curve to both input ports, one named "C" and the other named "A"*
- *Connect the tangent vector curve to both input ports, one named "B" and the other named "C"*
- *Pick an element called "Text Tag" from the "Display" tab and bring onto canvas*

- Connect from the output port named "P" to input port named "L" on "Text Tag"

- Connect from the output port named "D" to input port named "T" on "Text Tag" to display degrees of angles of deviation on trajectory curves.

- Pick an element called "Panel" and bring onto canvas

- Connect from the output ports named "D" to see the degrees of angles of deviation on trajectory curves

Postcondition: *Angles of Deviation at designated points on trajectories are listed*

4.3.2.6. Intersecting Trajectory Lines 

Within spatial layout evaluation methodology, not all trajectories are recorded simultaneously. They may be recorded with or without temporal data in different cases. This operation gives the user the ability to discover intersections of trajectories in the form of points (coordinates) and zones (cells) within the layout that they analyze (Figure 12). Points and zones, therefore indicate overlapping routes at certain instances. *Bumping into each other within an adequate space* may imply *bottlenecks* within plan layouts. Therefore, intersecting trajectory lines are considered among indications of layout problems. It is one of the essential operations of this framework that can compute intersecting trajectory lines within layouts.

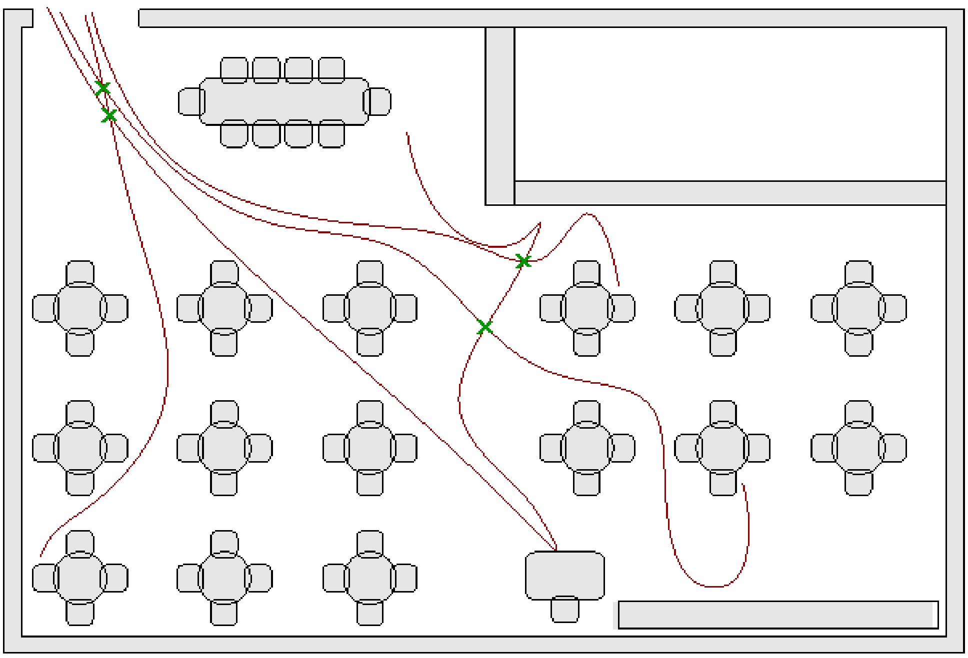


Figure 12. Sample layout displaying OLIA tool "Intersecting Trajectory Lines"

OLIA is also able to extract lists of intersection point coordinates as well as how many times or when routes overlap. This list allows users with the ability to process data on their own terms. However, although time is already included in this framework implementation of an operation yielding temporal output as a list for when intersections happen is envisioned as future work and left out of the scope of this dissertation.

Name: *Intersecting Trajectory Lines*

Description: *An operation that finds the points where trajectories intersect*

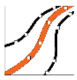
Precondition: *User should have created trajectories within Rhino/Grasshopper environment*

Flow of Events: - *Have trajectories already created as "Curves"*

- *From OLIA tab on the component palette, pick component called "Crash" and bring onto canvas*
- *Connect the trajectory curve to find intersecting trajectories for to input port named "C"*
- *Pick an element called "Panel" and bring onto canvas*
- *Create a number slider to connect to the input port named "i" to pick the index of which inflection points to view*

Postcondition: *Intersections on trajectories are listed*

Coordinates of intersection points are listed

4.3.2.7. Average of Trajectories 

Computing the averages enables controlled simplification of trajectory data for layout evaluation framework. Average of trajectories is an operation that allows the user to see bulk or cluttered trajectory data in a simplified and controlled fashion. This operation computes midpoints of corresponding points on the trajectory curves that are being averaged(Figure 13) The curves to go through this operation are divided into equal number of points and the average curve goes through points that are computed as midpoints.

When data is acquired in huge quantities it requires aggregation during data preprocessing. Although most aggregation process runs in databases it is anticipated that graphical aggregation of trajectory data will also be operational. In the case of manual acquisition of trajectory data through tracking occupants, it also enables uncovering and simplifying visual interpretation of trajectory data.

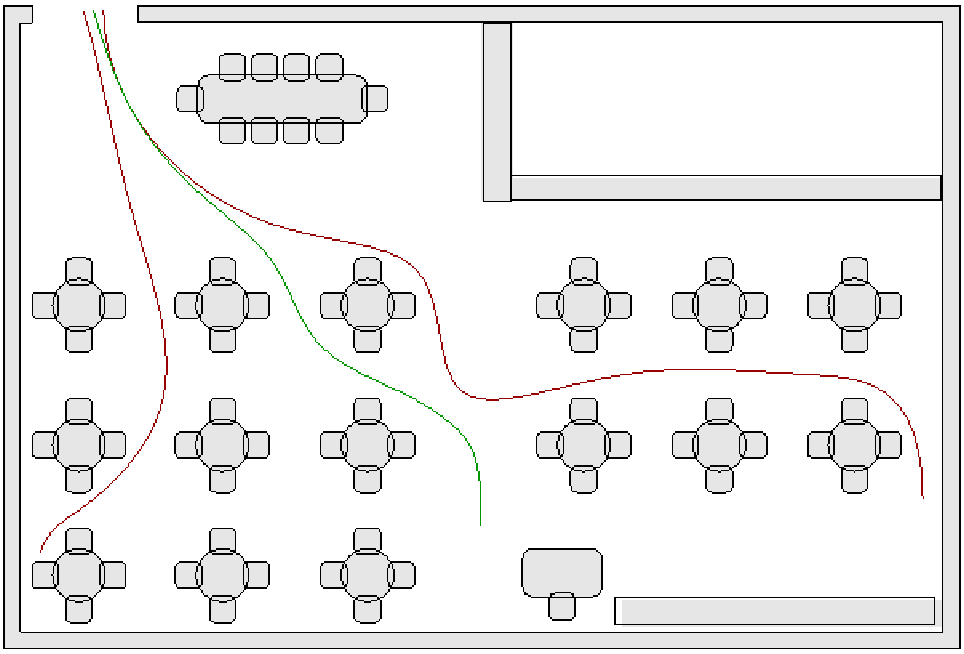


Figure 13. Sample layout displaying OLIA operation "Average of Trajectories"

Average of trajectories does not specifically create designated or manipulated routes as a result of this operation. However, it indicates and/or suggests certain possibilities to the user when evaluating layouts. The results that are in the form of trajectories may pass through unassigned and non-practical routes. However, by restricting the emergent curves in terms of avoiding layout elements, it is possible to obtain new trajectories.

Name:	*Average of Trajectories*
Description:	*A tool to view curves formed when two or more trajectories are averaged*
Precondition:	*User should have created trajectories within Rhino/Grasshopper environment*
Flow of Events:	*- Have trajectories already created as "Curves"*
	- From OLIA tab on the component palette, pick component called "Average of Trajectories" and bring onto canvas
	- Connect the first trajectory curve to input port named "C"
	- Create a number slider to connect to the input port named "i" to pick the index of division on curve
	- Connect the second trajectory curve to the other input port named "C"
	- Create a number slider to connect to the input port named "i" to pick the index of division on the second curve

- Create a third number slider to connect to the input port named "i" to pick the index of division for the average curve and set it to "1"

- Pick an element called "Curve" and bring onto canvas

- Connect from the output ports named "C" to see the curve formed as the average trajectory

Postcondition: *An average trajectory curve should have formed*

4.3.2.8. Definition of Loop 

To run operations on loops forming within trajectories a tool to define a "loop" is needed. Operations involving loops is based on definition of loop as self- intersections of trajectory curves. However, loops that do not intersect can also be the case in trajectory analysis. There might be instances when looping behavior may come very close to intersection and do not meet. Therefore analyses need definitions for setting up tools to count loops. Currently, the definition of loop is set to a closed loop (Figure 14). However, more definitions can be added to OLIA as new cases require more detailed and precise analyses. For example, the proportion of the dimensions of a loop compared to the dimensions of layout can be set to a threshold value to rule out some of the loops that are forming during navigation.

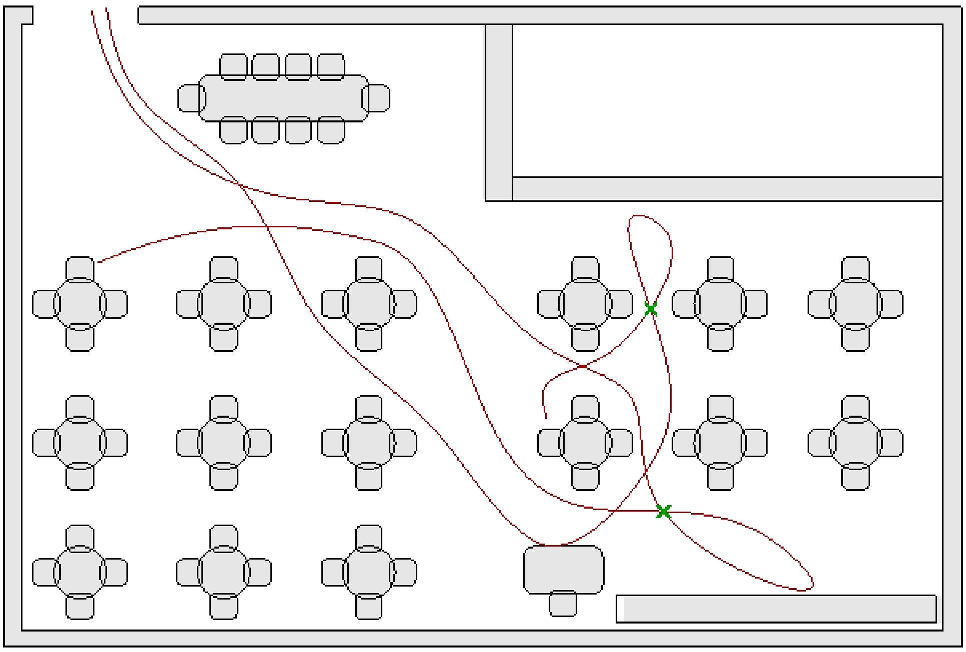


Figure 14. Sample layout displaying OLIA tool "Definition of Loop"

Closed loop is displayed with the point where the paths overlap themselves. In future studies the operation will also be improved to yield information on the lengths of loops since that parameter might also give the user insights on how long it takes occupants to realize that they might be going the wrong direction etc.

Loops on trajectories are interpreted as indications of returning to where the occupant comes from. Therefore, it is considered in TDPF as signaling a possible layout problem such as wayfinding. Depending on how often it is repeatedly seen in a certain space will contribute to understanding whether there is such a layout problem in that space.

Name:	*Definition of Loop*
Description:	*A tool to set the definition of loop. Currently, it is set to a closed loop intersecting itself. Outputs a list of points where loops form on trajectories*
Precondition:	*User should have created trajectories within Rhino/Grasshopper environment*
Flow of Events:	*- From OLIA tab on the component palette, pick the element called "Definition of Loop" and bring onto canvas*
	- Connect the trajectory curve to find looping points for to input port named "C"
	- Create a number slider to connect to the input port named "i" to pick the index of which loop to view
	- Pick an element called "Panel" and bring onto canvas
	- Connect from the output ports named "S"to the Panel element to see the coordinates of looping points
Postcondition:	*Looping Points on trajectories are listed*
	Coordinates of looping points are listed

4.3.2.9. Number of Loops 

This operation is for counting how many loops form on trajectories based on the definition of loop given by the user.

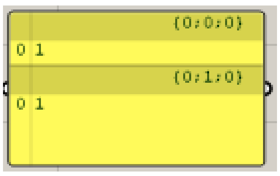


Figure 15. Sample list displaying OLIA operation "Number of Loops"

Number of Loops yields lists of quantity values for loops forming on each trajectory separately (Figure 15). The resulting numbers are evaluated based on threshold values determined by the user of OLIA. As stated earlier, the number of loops formed on trajectories showing occupant navigation behavior indicates possibilities of difficulty in wayfinding.

Name:	*Number of Loops*
Description:	*A tool to count how many loops form on one or more trajectories, for curve analysis purposes*
Precondition:	*User should have created trajectories within Rhino/Grasshopper environment*
Flow of Events:	*- Have trajectories already created as "Curves"*
	- From OLIA tab on the component palette, pick component called "Number of Loops" and bring onto canvas
	- Connect the trajectory curve to count the number of loops to the port named "C"
	- Pick an element called "Panel" and bring onto canvas
	- Connect from the output ports named "L", "Panel element to see the quantity of loops
Postcondition:	*Number of loops on trajectories are listed*

4.3.2.10. Number of Occupants 

Based on trajectory data, it is possible to calculate how many occupants use each location in a specific space (Figure 16).This data can be processed in terms of counting the number of people per cell. Counting number of occupants per cell gives information on density varying based on resolution. *Resolution* is defined by grid dimensions used in the operation of counting occupants.

In Rhino/GH, trajectory curves are defined as intersecting entities with a grid that enables resolution management. Cell dimensions can be altered by the user of OLIA package. Each cell represents number of occupants stepping in those cells the dimensions of which can also be interpreted as the resolution of that spatial layout.

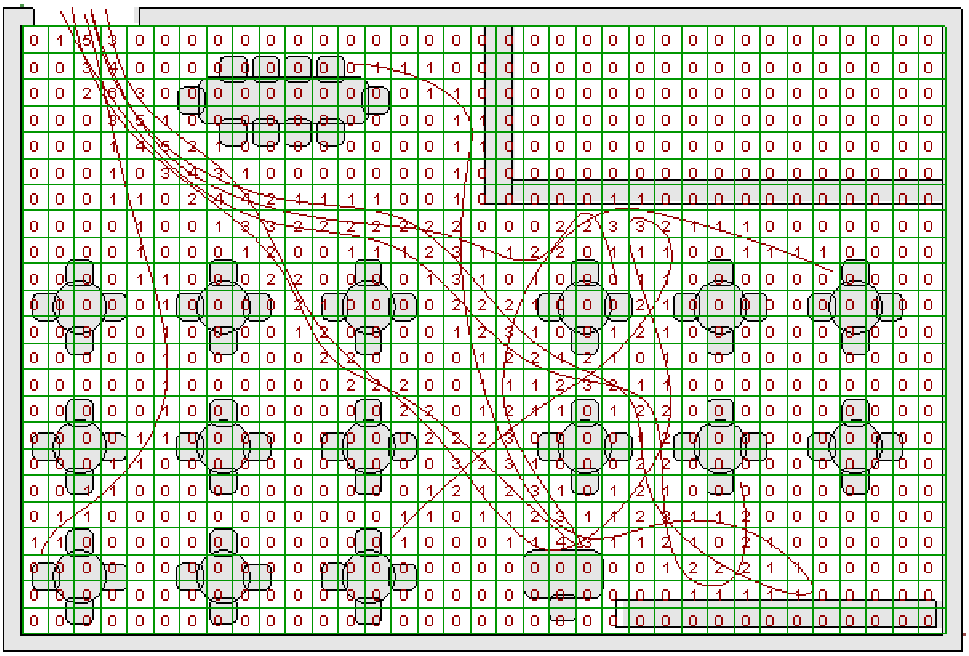


Figure 16. Sample layout displaying OLIA operation "Number of Occupants"

Name: *Number of Occupants*

Description: *A tool to count how many occupants used a specific zone based on trajectory curves occupying surfaces divided at specific resolutions, for curve analysis purposes*

Precondition: *User should have created trajectories within Rhino/Grasshopper environment*

Flow of Events: - *Have trajectories already created as "Curves"*

- *From OLIA tab on the component palette, pick component called "Number of Occupants" and bring onto canvas*

- *Connect the trajectory curves to find number of occupants to input port named "B"*

- *Create number sliders to connect to the input ports named "Sx" and "Sy" to adjust size for resolution.*

- *Create number slider to connect to the input ports named "Ex" and "Ey" to adjust grid for resolution.*

- *Pick an element called "Polygon Center" and bring onto canvas*

- *Connect from the output ports named "C" to the Polygon Center element with input port "P"*

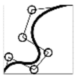
- *Pick an element called "Panel" and bring onto canvas*

- *Connect from the output ports named "L" to the panel*

- *Pick an element called "Tag" and bring onto canvas*

- *Connect from the output ports named "L" to "Tag"*

Postcondition: *Inflection Points on trajectories are listed,*
Coordinates of inflection points are listed

4.3.2.11. Checking Control Points 

OLIA serves as an analysis package that enables its user with several options in analyzing occupant trajectories. This tool gives the user the ability to see and control the points that each trajectory is interpolated with. Furthermore, with the help of this tool called *checking control points*, the user can play with trajectories and visualize alternative trajectory options (Figure 17).

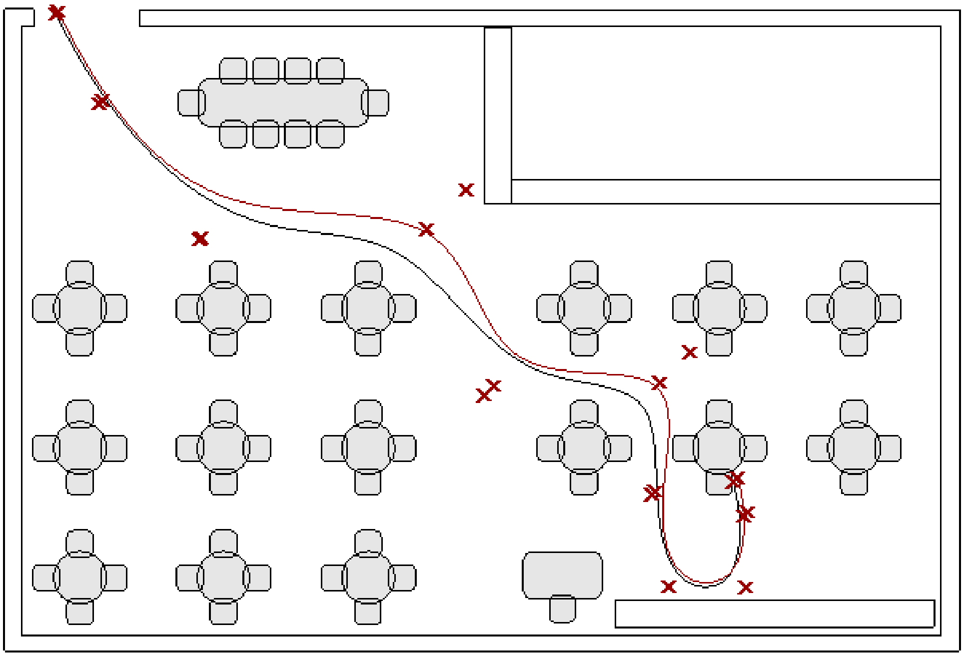


Figure 17. Sample layout displaying OLIA tool "Checking Control Points"

The tool can help the user test alternative layout organizations and apply OLIA tools and operations on their new layout suggestions. They may as well evaluate alternative output values compared with threshold values of their own.

Name: *Checking Control Points*

Description: *A tool to view changing output values when trajectory curves change on layouts. Changes in curves are manipulated with control points*

Precondition: *User should have created trajectories within Rhino/Grasshopper environment*

Flow of Events: - *Have trajectories already created as "Curves"*

- *From OLIA tab on the component palette, pick component called "Checking Control Points" and bring onto canvas*

- *Connect the trajectory curve to find inflection points for to input port named "C"*

- *Pick an element called "Gene List" and bring onto canvas*

- *Connect from the output port to input ports named "X", "Y" and "Z" on the "Checking Control Points" element to see the coordinates of control points*

- *Pick an element called "Curve" and bring onto canvas*

- *Connect "Checking Control Points" element from output port "C" to the Curve element*

Postcondition: *Curve from alternative control points is created*

4.3.2.12. Time Data Entry 

While creating trajectories on layouts temporal data is entered (Figure 18). Although some of the analysis tools and operations do not involve or require time as data, it is definitely essential to enable time data entry into the analysis.

Enabling time data entry tool enables the user to analyze speed adding dimensions to the semantics of spatial evaluation framework. Having access to how much time is spent in which specific zone enables the user with deeper insights. These insights include understanding the flow of navigation within space and may reveal slowing factors if any come into play.

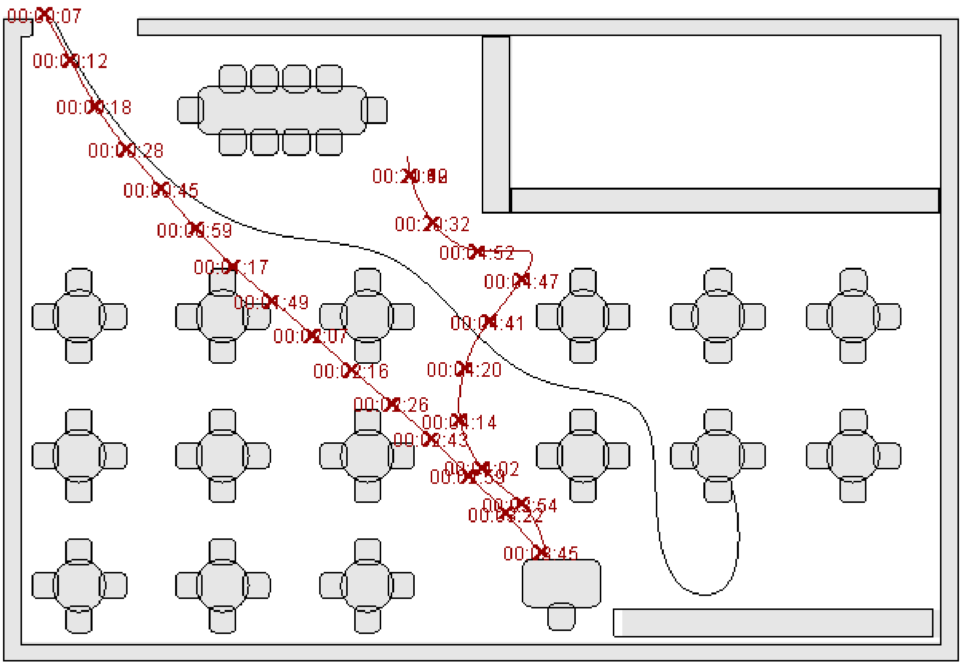


Figure 18. Sample layout displaying OLIA tool "Time Data Entry"

Name: *Time Data Entry*

Description: *A tool to enter and view time data for trajectories.*

Precondition: *User should have trajectories already created as lists of coordinates from trajectories recorded at specific distances eg. 1 m.*

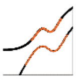
User should have corresponding time data for trajectories already created as lists of coordinates recorded at recorded distances on trajectories.

Flow of Events: - *Pick an element called "Panel" and bring onto canvas*

- *Enter coordinates list of Location Data into the panel*
- *Pick an element called "Panel" and bring onto canvas*
- *Enter coordinates list of Time Data into the panel*
- *From OLIA tab on the component palette, pick component called "Time" and bring onto canvas*
- *Connect the trajectory coordinate list in Panel to input port named "V"*
- *Connect the time list in Panel to input port named "Time"*
- *From OLIA tab on the component palette, pick component called "Curve" and bring onto canvas*
- *Connect the output port named "C" to the element "Curve"*
- *From OLIA tab on the component palette, pick component called "Tag" and bring onto canvas*
- *Connect the output port named "P" to input named "L" on "Tag"*
- *Connect the output port named "T" to input named "T" on "Tag"*

Postcondition: *Trajectory curve/s are created*

Curves are tagged with time data

4.3.2.13. Speed 

With OLIA it is possible to calculate speed based on the method that trajectories are created and analyzed timewise. Once the timestamp and coordinate data has been captured, speed tool (Figure 19) can be used.

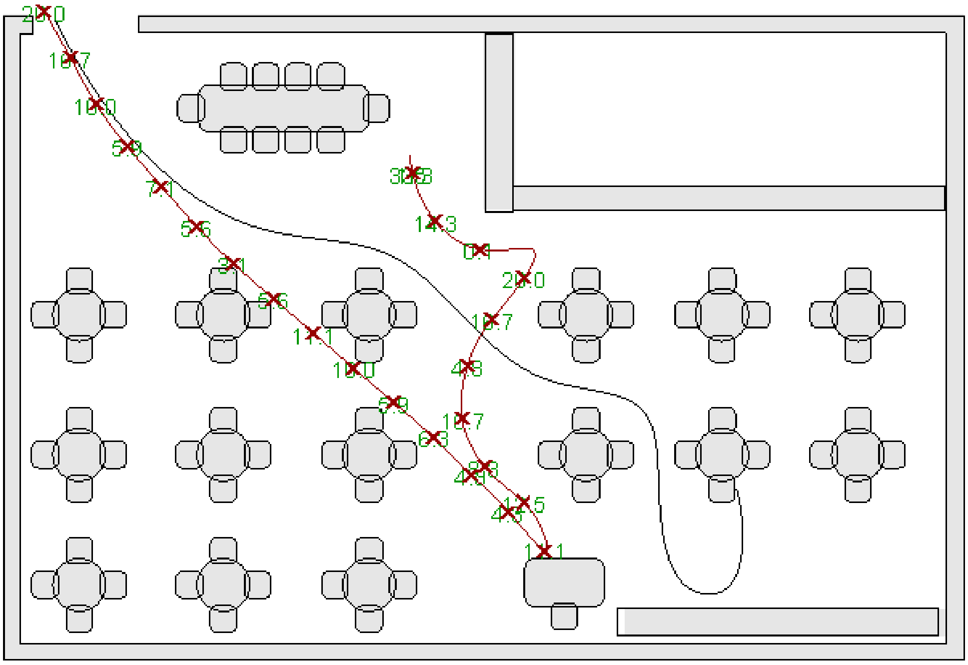


Figure 19. Sample layout displaying OLIA operation "Speed"

Comparing with the values of expected navigation speed for certain zones in certain spaces, users of OLIA may find out about possible *bottlenecks* as layout problems. This is done by following the slowing down behavior within that space. At the incidence of slowing down the user may search through possible reasons and additional analysis such as closest proximity and may further their research for alternative layout organizations.

Name: *Speed*

Description: *A complementary tool to enter and view speed data for trajectories.*

Precondition: *User should have trajectories already created as lists of coordinates from trajectories recorded at specific distances eg. 1 m.*
User should have corresponding time data for trajectories already created as lists of coordinates recorded at recorded distances on trajectories.

Flow of Events: - *Pick an element called "Panel" and bring onto canvas*

- *Enter coordinates list of Location Data into the panel*
- *Pick an element called "Panel" and bring onto canvas*
- *Enter coordinates list of Time Data into the panel*
- *From OLIA tab on the component palette, pick component called "Time" and bring onto canvas*

- Connect the trajectory coordinate list in Panel to input port named "V"

- Connect the time list in Panel to input port named "Time"

- From OLIA tab on the component palette, pick component called "Curve" and bring onto canvas

- Connect the output port named "C" to the element "Curve"

- From OLIA tab on the component palette, pick component called "Tag" and bring onto canvas

- Connect the output port named "P" to input named "L" on "Tag"

- Connect the output port named "T" to input named "T" on "Tag"

- From OLIA tab on the component palette, pick component called "Speed" and bring onto canvas

- Connect Time entry list panel to input port named "Time"

- Connect Distance entry list panel to input port named "A"

- Connect Speed element from output port named "R" to input named "T" on "Tag"

Postcondition: *Trajectory curve/s are created*

Curves are tagged with time and speed data

Speed between vertices are listed

CHAPTER 5

CASES

5.1. Overview

As mentioned previously, TDPF defines a statement for occupant movement within architectural space and provides a set of analysis tools for processing collected data. Development of a research platform to support efforts on quantitative evaluation of space layouts is aimed. To illustrate, data collected in three public spaces with similar typology in three different university campuses is analyzed in this research. All of these spaces are the same scale and they are among the most visited spaces within the buildings that they serve. The tools and framework developed in this research are applicable to various spaces. However, the research cases were chosen to be within similar scale so that additional criteria that would affect the scope could be eliminated. Alternative cases for analysis would be a wide variety of service spaces such as transportation hubs, offices, malls, production facilities, hospitals, and educational buildings rather than residential architectures.

The tools and the knowledge base developed within this research can also be applied to outdoors since OLIA is based on two-dimensional analysis of trajectory data. Nevertheless initial work field was picked as an indoor space since it provides a comparably more controllable case analysis of layouts.

Three cases are analyzed. Case I is a café in Izmir Institute of Technology (IYTE) campus where it mainly serves members of Architecture, Industrial Design and Urban Planning departments. The second case that ran in campus café of Yaşar University (YU) is also analyzed with OLIA to demonstrate how users can view outputs. In case III, Faculty of Fine Arts Café in Izmir University of Economics (IUE) was analyzed. In case III, there are two different layout alternatives. The two alternatives are compared within that case. Additionally, the work done on case III is deepened by a questionnaire through which more than 100 occupants/customers of the place are surveyed on their perception of the café and asked if they identify possible layout problems.

As previously indicated, the processing environments of collected data is classified as *cell-based data processing environment* and/or *vector-based data processing environment.* Cell-based environment utilizes a grid of cells for processing location-based data. Cells are filled based on number of times they are visited with variations depending on designated resolution. In case I, data is processed in cell based environment. Case II displays analysis of trajectories through OLIA and is implemented in *vector-base*. In case III, data is processed in both options and *vector-based* trajectory data using splines is then analyzed through OLIA for trajectory analysis.

5.2. Case I: IYTE Campus Café

5.2.1. Subjective Evaluations

In this case in order to determine if analyzing and understanding space based on the objective data collected is useful, the space is discussed with a panel of experts. The panel's evaluation is later compared to the actual usage data collected. An expert panel of architects who are also academicians and regular occupants of this space was formed. The panel is asked to define problems for the plan layout and suggest solutions for them. The experts are surveyed by handing out the present plan layout of the café. They are asked to draw most commonly used trajectories of occupants based on observation (Figure 20). On a second sheet, they are requested to sketch their revision suggestions for the layout problems that they had observed and/or experienced within this space.

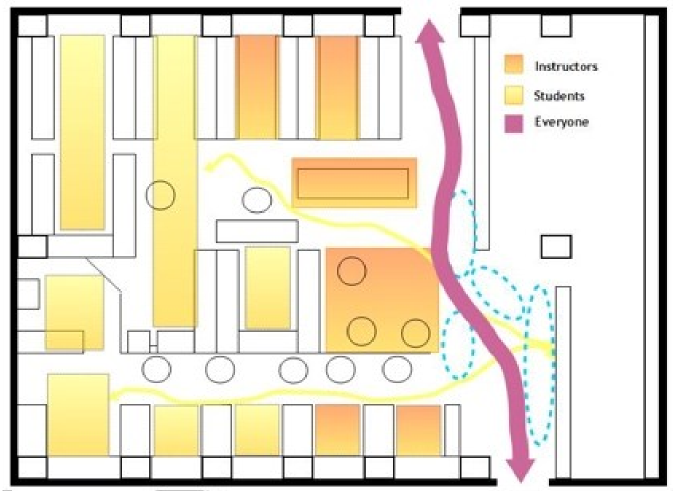


Figure 20. IYTE Campus Café analysis by an architect

The panel indicated that the entrances were off-center compared to the natural flow expected and that:

A) space is not used efficiently and

B) the inner entrance is too crowded to function as both a purchase point and an entrance.

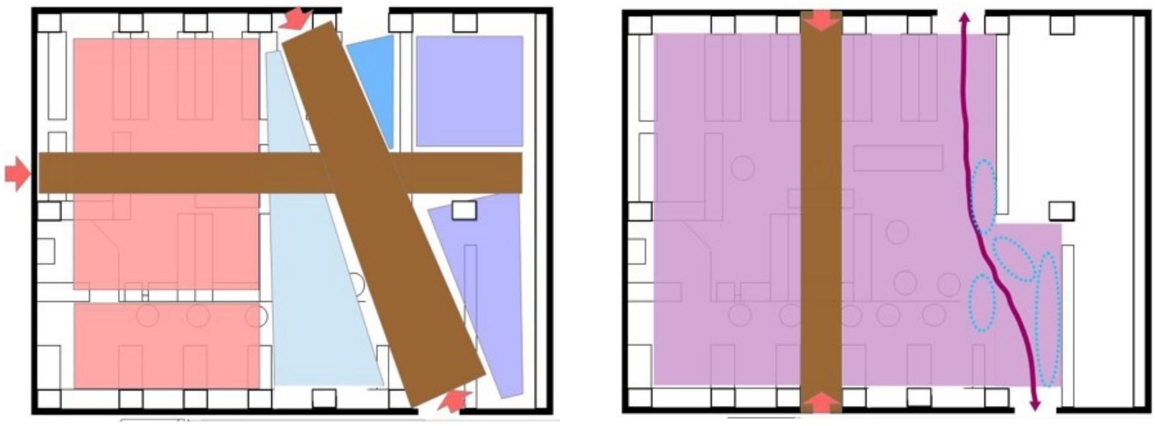


Figure 21**.** IYTE Campus Café- Suggestions by Expert Panel

When reviewed, the panel has mainly suggested entrance alternatives. Later, the architects are asked to propose alternative designs. The two sketches of the same space representing their suggestions is given in Figure 21. Both suggestions are based on the tacit knowledge of the experts upon observing the layout and occupants. Later, the objective approach is employed with *data acquisition*, *trajectory analysis* and *behavior interpretation* phases.

5.2.2. Data Acquisition

The initial data collection for tracking occupant movements is done through capturing videos from a café in IYTE campus (Figure 22). Occupant movements within these spaces are recorded and then analyzed. With this method occupant trajectories are expected to be automatically plotted on plan layouts. The technology required for this capability called *computer vision* is not utilized within these case studies since this technology is not the main focus of this research. The main focus is not on how data is collected but rather on how it is processed and analyzed.

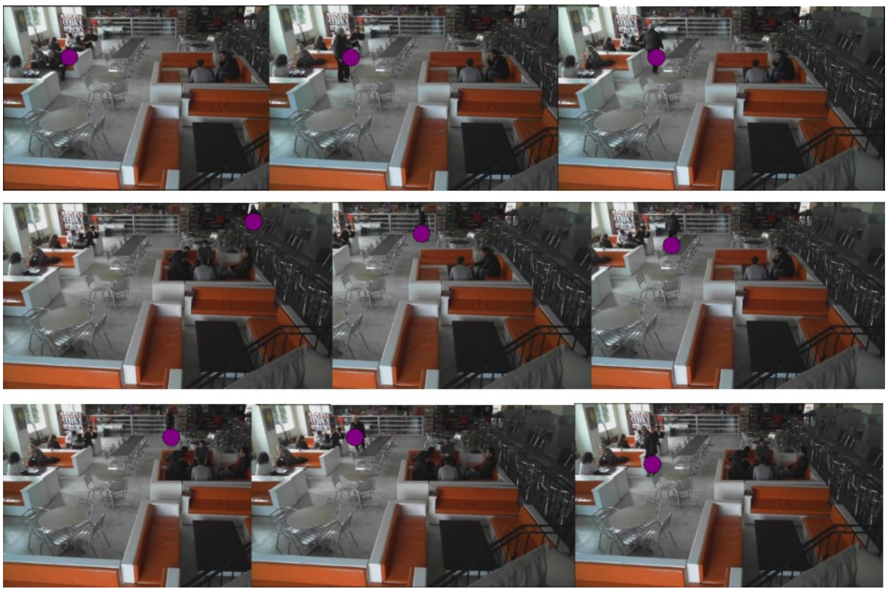


Figure 22. IYTE Campus Café: Frames extracted from video recording

5.2.3. Trajectory Analysis

The captured video data in the IYTE Campus Café is manually processed and analyzed as trajectories represented in the form of *cell-based* data. Each occupant trajectory through the space is recorded on a grid of cells for tracking location information.

Figure 23. Grid of cells for tracking location information IYTE Campus Cafe data

In this case, main data is processed into *cell-based* (MS Excel was used in this case study) environment. Through data processing, the trajectory data obtained from

IYTE Campus Café is manually fed and counted. The patterns formed on Excel interface is analyzed based on information placed. (Figure 23) Trajectory data which is called *the main data* collected, creates patterns, when fed into cells.

5.2.4. Behavior Interpretation

Since Trajectory Data Processing Framework is constructed to facilitate semantic translation of raw occupant movement data acquired through observation, analyzing and comparing navigation patterns in *cell-based* environments is considered one option for architectural plan layout analysis using occupant navigation.

Based on visualization of occupant navigation patterns, it can be viewed that the space has zones that are *over-crowded* or that there is a problem of *wasted space* in this spatial layout. Both expert evaluation remarks- *space is not used efficiently* and *the inner entrance is too crowded to function as both a purchase point and an entrance* – can be viewed from the patterns formed on the layout that is analyzed.

5.2.5. Performance Evaluation

Analysis results for Case I displays dense areas and a general navigation pattern for certain time periods. *Cell-based* data gives the information that those cells are occupied during several data acquisition sessions. Therefore, this case is a brief example of how the process would be if occupant tracking is to be done through video capture. *Cell-based* data entry and analysis is still an option in this research platform however graphical processing of data is discontinued.

Most expert response displays that the layout is not favored by the experts and they have several different solutions for how the space should have been designed. When reviewed, it can be seen that the objective data acquired through tracking of occupants does match the evaluation of experts.

For quantitative evaluation the criteria for any specific layout problem, in this case *density*, the units for counting occupants per a specified area per time such as *No. of Occupant/m2/min*, and threshold values such as *>X occupants* need to be set.

This case utilized MS Excel for analysis. The next two cases display how vector-based data entry is used and how collected data is processed within the OLIA plug-in for Rhino/Grasshopper.

5.3. Case II: Cafeteria/Dining Hall of Yaşar University

Case II is another service space with similar function and is also the busiest space on campus within specified hours. Cafeteria/Dining Hall of Yaşar University (YU) has a capacity of serving 400 people. However, there are two floors and they function differently although they have common services for students, faculty and staff. Entry level serves between 8:30-18:00 as café and dining hall (Figure 24). The upper floor of cafeteria serves only between 11:30-14:00. It has one entrance/exit.

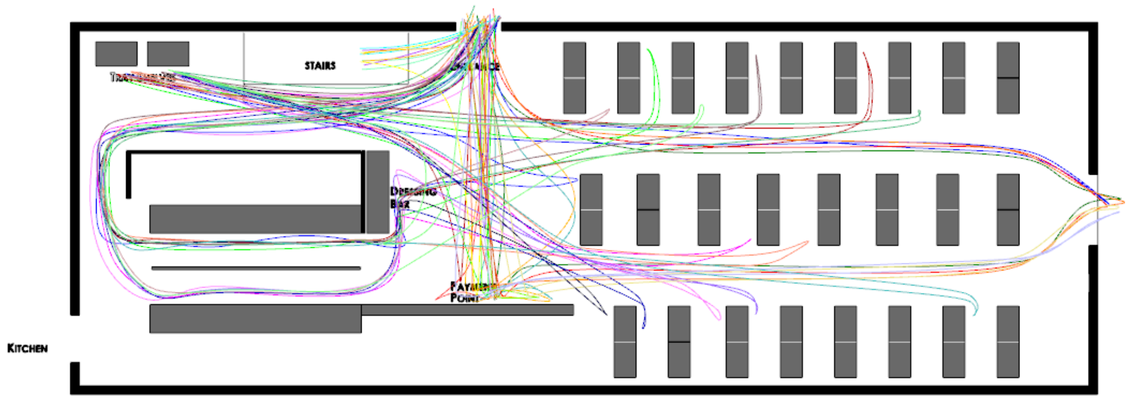


Figure 24. YU Campus Café/Dining Hall, Ground Floor

5.3.1. Data Acquisition

Occupant trajectories numbered around 150 are manually recorded. These 150 trajectories represent occupant navigation with various purposes. Some of them are targeted for direct purchase points and such navigation is classified as *transiting* within TDPF analysis. In this case, data is entered directly into computer in *vector-based* format.

5.3.2. Trajectory Analysis

For brevity, only visually manageable amount of data is shown in figures captured from OLIA. For example, in the upper floor, 20 of the 150 trajectory data can be seen as splines analyzed in OLIA. Two examples of visual feedback provided by OLIA for case II can be viewed below.

Example for Number of Occupants - Figure 25 displays numeric feedback on most *crowded* zones in upper floor. The cells are formed based on a grid of 80 cm laid on this spatial layout. These cells carry the numeric values for how many times they are occupied within the duration of observation. The highest numbers indicate that they are the ones to be stepped on.

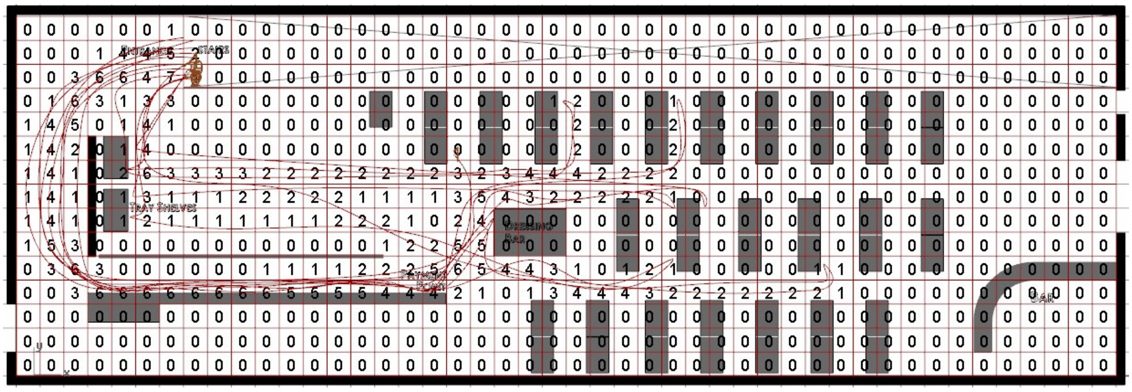


Figure 25. YU Campus Café/Dining Hall, Upper Floor, Counting number of occupants with OLIA at a resolution of 80 cm on occupant navigation layer

Example for Closest Proximity -Figure 26 shows visual feedback of *closest proximity* for one occupant trajectory interacting with the layout. The tool outputs coordinate data on instances where two entities are closest, one being the trajectory and the other is the whole layout elements defined as one set of curves. Distances for the closest proximity instances are also listed as output as seen in Figure 27

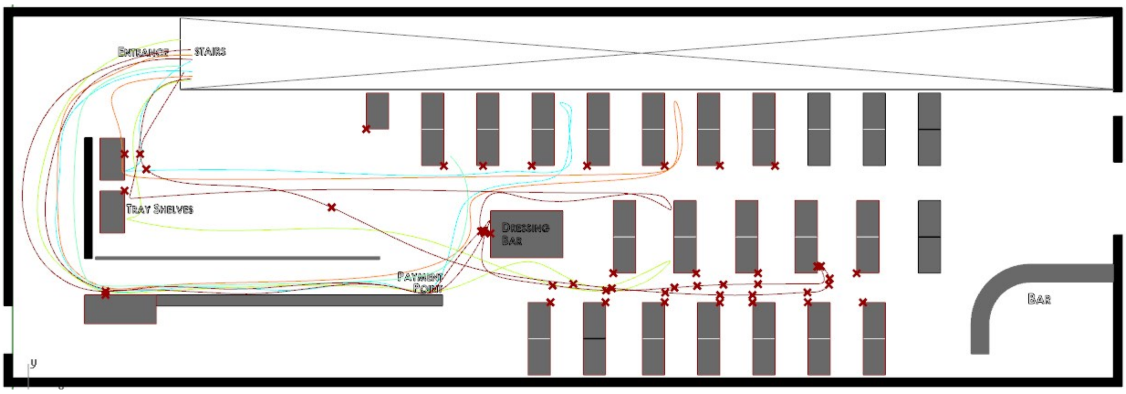


Figure 26. YU Campus Café/Dining Hall, Upper Floor- Checking Closest Proximity with OLIA at a resolution of 80 cm on occupant navigation layer

Example for Intersecting Trajectories - This space is analyzed in terms of encounters that is *intersecting trajectories* and the pattern can be viewed in Figure 28. For this analysis 38 trajectory curves are processed. The busiest zones within the layout can be seen by the accumulation of red dots shown on the layout that is analyzed.

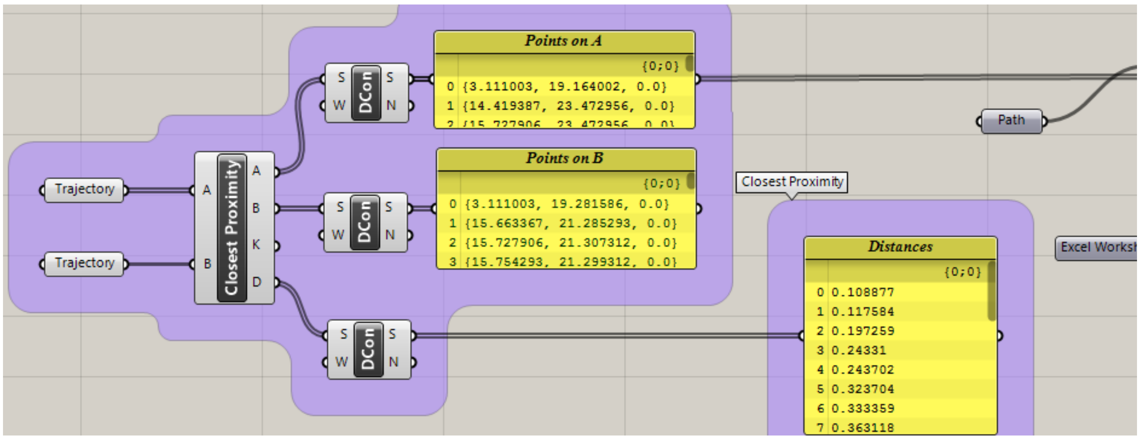


Figure 27. YU Campus Café/Dining Hall, Upper Floor- Output lists yielded from Checking Closest Proximity with OLIA at a resolution of 80 cm

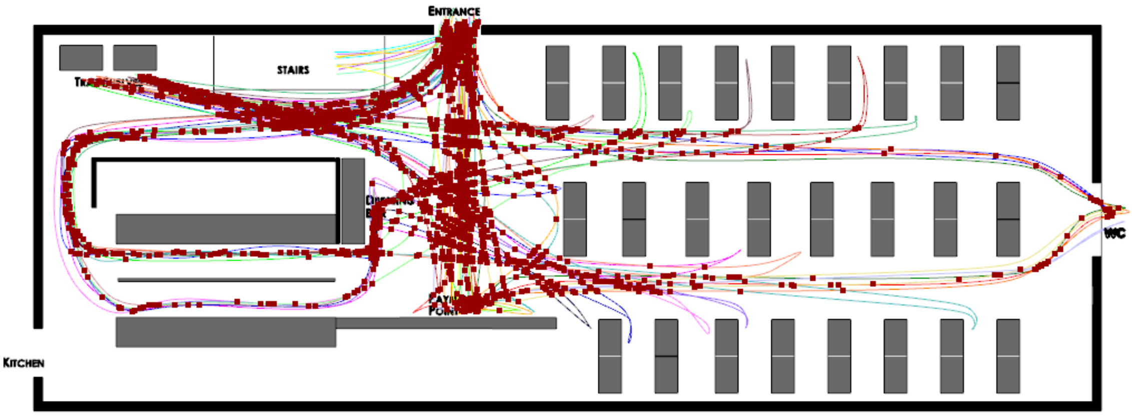


Figure 28. YU Campus Café/Dining Hall, Ground Floor. Intersecting trajectories tool of OLIA

5.3.3. Behavior Interpretation

Although this analysis is based on 2D navigation data ruling out *time*, the stained areas are most likely to see instances of *bumping into each other* as a layout problem. Both floors are quite similar in their layout organizations and the number of customers they are serving for. However, the fact that the ground floor has a sales point that is a direct target for users at all times does make a difference in use patterns (Figure 28) between two spaces. In the ground floor, the direct reach to purchase point creates a path that crosses other paths whereas the upper floor does not have such a path. This can be viewed from analysis outputs both graphically and numerically (Figure 27). *Transiting* (only passing through the space without stopping) is negligible in the upper floor since *transiting* is only for reaching VIP hall and toilets. However, on the ground floor where the café is situated, *transiting* is not negligible since toilets are also used by occupants of the campus that are not necessarily users of either the café or the dining services of this field. Therefore semantic interpretation with TDPF of reasons for similarities and differences is needed for elaborate evaluation of this space.

5.3.4. Performance Evaluation

The ground floor of YU Campus Café/Dining Hall is a service space that functions from 08:30 to 18:00. Although it is a very busy space it has a smooth flow at all times. When services are considered the space seems very adequate when compared to its physical capacity. For a robust evaluation of performance, thresholds are needed. For example, for the case of *bumping into each other,* based on the capacity of a space being analyzed, there is a threshold of people that can pass through a certain zone within a designated time interval. The problem occurs when that threshold is reached. This data is held in future research results. Therefore, users can set their own values and reach their own performance evaluation ratings based on the operations run on trajectories.

5.4. Case III: IUE campus café

Case III is in another location that is a service space with similar scale as *Case II*. This space has access to both outdoors and indoors as in *Case I* and is one of the busiest spaces on campus; Faculty of Fine Arts Café of Izmir University of Economics (IUE). This space has a capacity of 60 seats. Also, during the research this place has been reorganized with a new layout and this is utilized as an alternative layout to analyze for the same space. This space has been analyzed with both manual tracking of occupants, an expert panel, and a questionnaire. The questionnaire and the expert inquiry are explained in the next section. Later, the subjective evaluations and objective data analysis results are compared.

5.4.1. Subjective Evaluations

During when the café had its previous layout organization, occupants/clients of FFA Café who were also design professionals and academics were gathered as an expert panel. They were surveyed by handing out two separate sheets on which the plan layout of the café was printed. On the first sheet, they were asked to draw most common trajectories of occupants based on observation and on their own behavior within the space in concern. On a second sheet, they were asked to draw their revision suggestions for the layout problems that they had observed and/or experienced within this space. As a result of this survey, most expert response is that the place does not need much modification. However, the layout is not favored by the same respondents either.

After modification of layout in FFA Café, this time, occupants are surveyed for their experience of the space using a questionnaire. Scale questions as well as short answer questions are used. Likert scale (Krosnick & Presser, 2010) ranging from 1 to 5 between "strongly disagree" and "strongly agree" is used. Visual material depicting the spatial layout of the café with a grid of zones is integrated with the questionnaire to help respondents to mentally trace their experiences of the place.

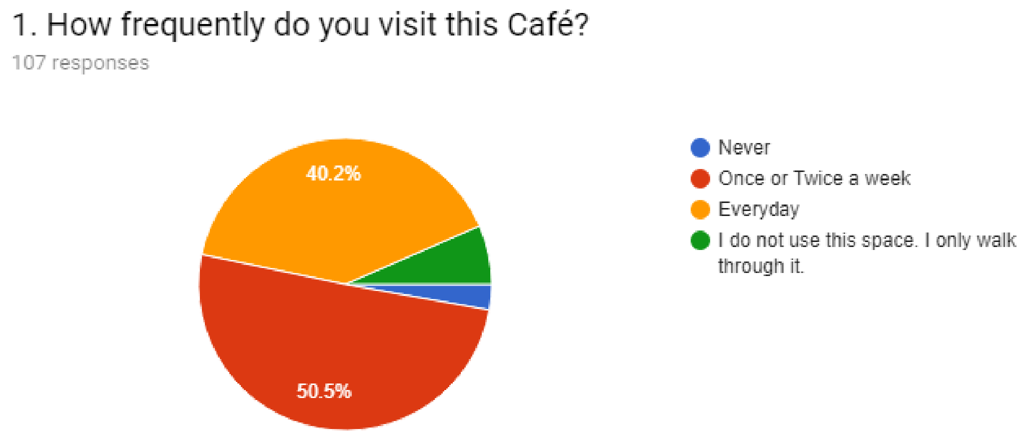


Figure 29. Frequency of Customer / Occupant Visits to the Café

13 questions were asked to customers/occupants of the café. 107 people responded to questions starting with how frequently they visit the place. Response options included *Never*, *Once or Twice a Week*, *Every day* and *I do not use this space* (Figure 29) Respondents who checked the first option were directed to the end or the questionnaire to submit their entries. The last option "I do not use this space" was used to allow customers who know but do not prefer to use the space due to several reasons, to express their layout related perceptions.

In the questionnaire, temporal information in hourly format was also collected. The graph in Figure 30 shows when the place is most frequently occupied based on the statements of respondents.

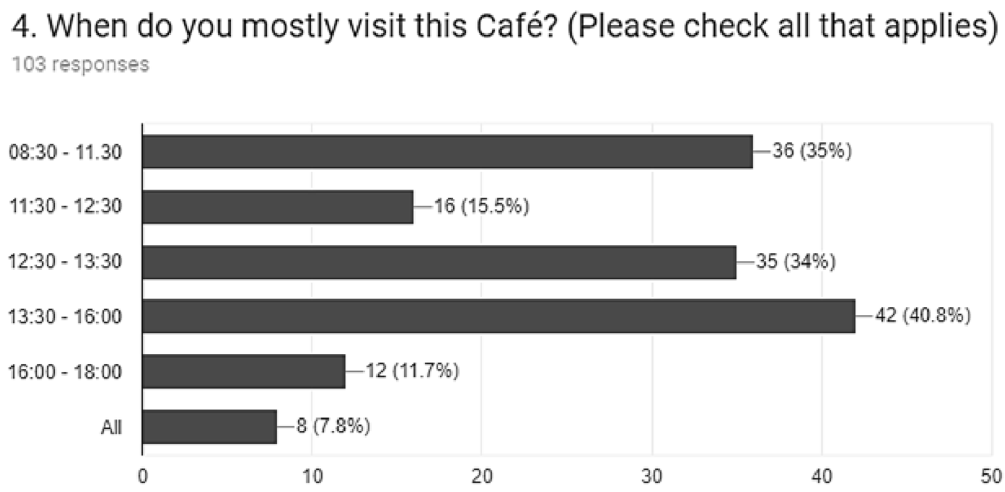


Figure 30. Hourly occupancy reported by Occupants

In the case of automated tracking of occupants, researchers can identify temporal occupancy levels through acquired data without having to inquire through occupants. However, this subjective information can be utilized at the beginning of a layout evaluation process to suggest periods for time-involved analysis.

Next question was the initial one concerning the clients' perception on possible layout problems that they observe in this space. The question allowed respondents to check as many choices as they could. The answers to this question carried the problem of *over-crowd* to the top. Second came the problem of *unpredictable usage of space* and third came *wasted space*. Following were the two equally voted problems that were *clutter*, *indirect access* and *bottlenecks*. Percentages of all possible layout problems that were voted for can be viewed in Figure 31 .

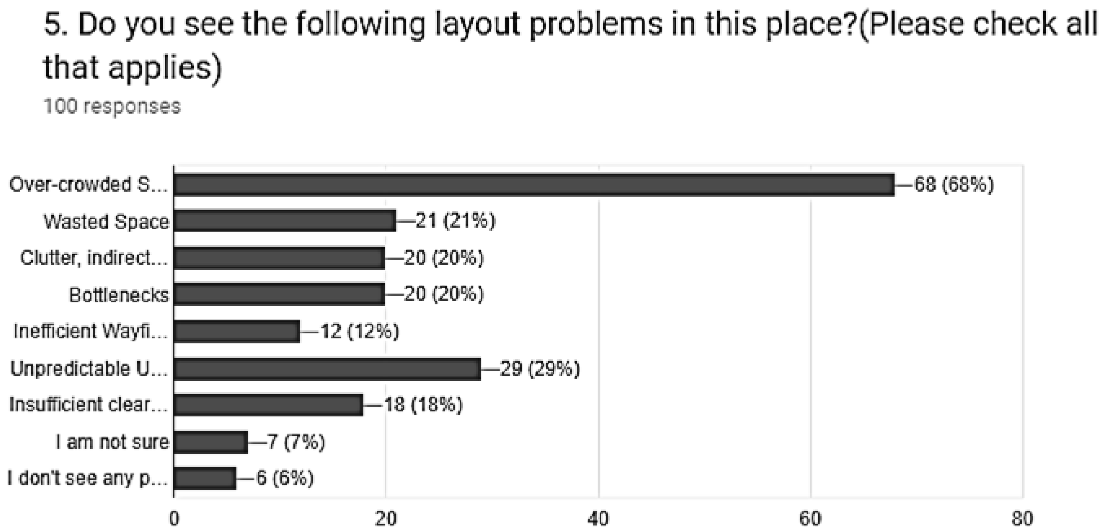


Figure 31. Occupant evaluation of Layout Problems

For the question number 7; "*I try to avoid certain areas in this place*", 86 responses were received. Some of these respondents did not indicate zones and some of them who did not enter rating responses did indicate the zones that they try to avoid. This responding behavior is among the initial motivations of this research. Some of the respondents who rated the place as neither *strongly agree* nor *strongly disagree* in terms of *avoiding certain areas within this space. However,* at the same time, the same respondents indicated 11 zones that they believe are problematic. When indicating zones, 65 respondents specified zone numbers.

Figure 32. Evaluation of Customers/Occupants for avoiding certain zones

Therefore responses of occupants depend mostly on their perception and may yield subjective results whereas watching patterns of behavior through tracking data may lead to more robust evaluation and understanding of their behavior within space. The resulting map for occupants' perception of zones that are being *avoided* can be seen in Figure 32 While *wasted spaces* were expected to match zones of avoidance, that was not the case as seen in Figure 33 when compared with Figure 32

Figure 33. Evaluation of Customers/Occupants for wasted spaces in some zones

Results of the questionnaire however displays that respondents indicated a similar pattern of zones to be *over-crowded* (Figure 34). This is interpreted as the occupants' avoiding behavior for *over-crowded* spaces. Thus if the respondents were literally avoiding the zones that they indicated to do so, then those very zones would not at the same time be indicated as the most crowded zones.

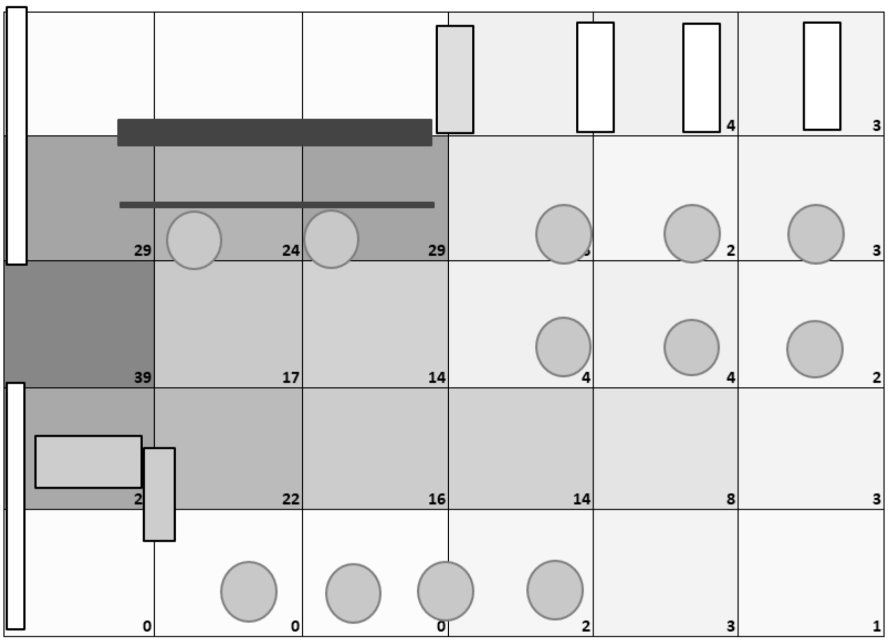


Figure 34. Evaluation of Customers/Occupants for accumulation at certain zones

Out of 100 people who filled out the questionnaire, 64% found the café quite satisfying in terms of spatial quality as can be viewed in Figure 35.

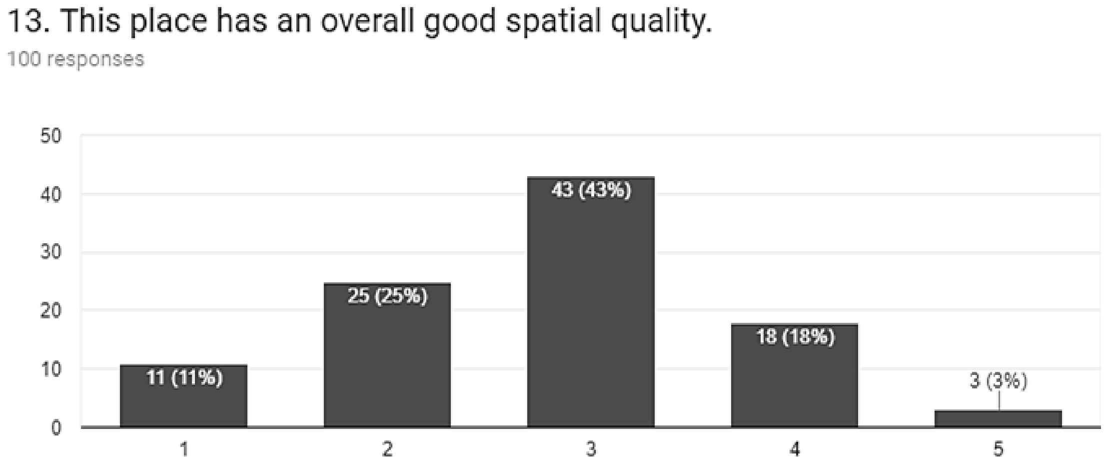


Figure 35. Response to the general evaluation comment for spatial quality

Navigation analysis in Case III is done in both data processing environments; cell-based and vector-based. Both data processing environments have previously been described in detail in *chapter three*.

5.4.2. Data Acquisition

During data collection, occupant trajectories numbered around 120 are manually recorded. Trajectory data that is manually collected in IEU campus café is fed into trajectory tables in Excel sheets (Table 10).

5.4.3. Trajectory Analysis

Cell-based data that also allows temporal data to be entered, stored and processed. Main data is also entered as *vector-based* trajectory data using splines. The previous layout of this space has been analyzed upon being processed as cell-based data. The current layout, though, is analyzed upon vector-based entry which may as well be entered as coordinates directly from excel sheets.

5.4.3.1. Cell-Based Data Processed Into Graphics, Lists and Tables

Cell-based data requires that there is a grid that navigation records in the form of trajectories can be fed into. Therefore, the trajectories are projected onto corresponding cells that belong to that grid. Trajectory data tables are used to compute navigation within

Table 10. Trajectory Data Table - IEU Campus FFA Café

Route11	Route12	Route 13	Route 14	Route 17	Route 18	Route 19	Route 20	Route 21	Route 22	Time		Time Interval		Speed	Route 23	Route 26
1	1	1	1	1	2	2	2	2		Entry	Exit	Stops	Runs		2	2
B7	B7	O13	O13	N13	S10	N13	O13	O13	O13	00:00.00	00:00.00	00:00.00			N12	N13
C7	C7	O12	O12	N12	R10	N12	O12	O12	N12						N11	N12
D7	D7	O11	O11	N11	Q10	N11	N12	N12	N11						M10	N11
E7	E7	O10	O10	M10	P10	M10	N11	N11	M11	00:03.19	00:05.07	00:01.88	00:03.19	0	L10	N10
F6	F6	O9	O9	M9	O10	L9	M10	M10	M10			00:00.00			K10	M10
G6	G6	P8	P8	L9	N10	K9	L9	L9	L10	00:07.22	00:10.89	00:03.67	00:02.15		J10	M9
H6	H6	P7	P7	K8	M10	J9	K9	K9	K10	00:12.55	00:17.05	00:04.50			I10	L9
H7	H7	P6	P6	K7	L10	I9	J9	J9	J10	00:18.87	00:24.86	00:05.99			H10	K9
G7	G7		P5	J6	K10	H9	I9	I9	I10	00:28.05	00:42.66	00:14.61			G10	K8
F7	G8		O5	I6	J10	G9	H9	H9	H10	00:45.78	00:56.73	00:10.95			F10	K7
E7	H9		O4	H5	I10	F9	G9	G9	G10	00:59.31	01:14.53	00:15.22			E10	J7
D7	G9		O4	I6	H10	E9	F9	F9	F10	01:17.54	01:43.71	00:26.17			D10	J6
C7	G7		O5	J6	G10	D9	E8	E8	E10	01:49.16	02:05.57	00:16.41			C10	I6
B7	F7		P5	K7	F10	C8	D8	D8	D10	02:07.45	02:14.60	00:07.15			C9	

plan layouts on each cell of different sizes at various resolutions. Data in the tables allow for several different resolutions during layout analyses.

Below is a layout on a grid of 1m² cells (Figure 36) Grid sizes can be manipulated based on user preferences. Resolution changes according to grid sizes and higher resolutions require more cells and therefore more data to be processed

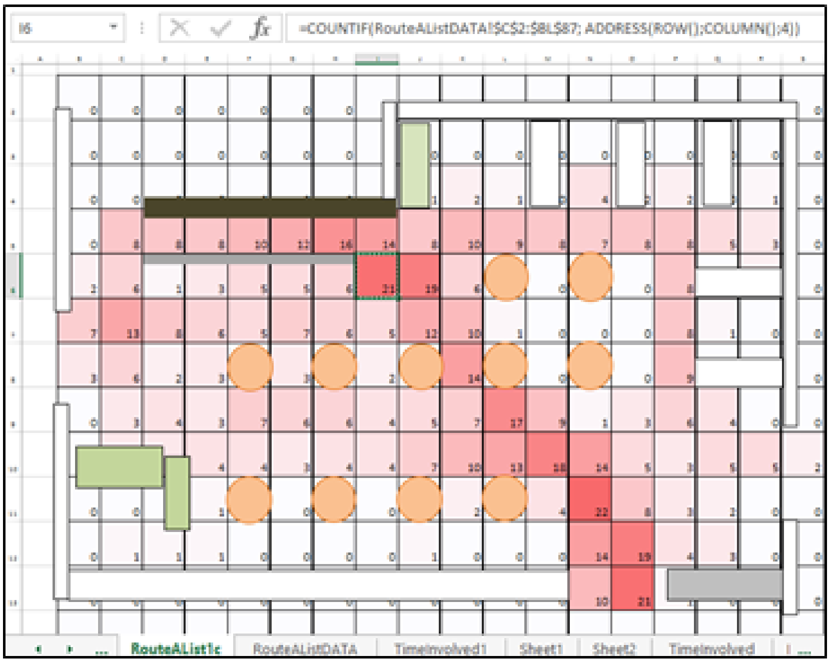


Figure 36. Plan Layout navigation density computed on cell resolution of 1 m² IEU Campus FFA Café

The graphical output displayed here shows the density pattern of this layout where most visited cells are colored as darkest. The computation used here is operated within Excel and uses the basic function *countif* to help count the number of occupants who stepped on each cell. This computation is applied on the previous layout of this café. Therefore it refers to probable *over-crowded* zones and *bottlenecks* based on the criterion of *density* in this place.

5.4.3.2. Main Data Processed Into Vector-Based Environment

As stated earlier, raw data is also entered as *vector-based* trajectory data using splines. Splines representing trajectories are comparably more suitable for OLIA tools and operations. However, OLIA tools provide both cell-based and vector-based analysis results depending on user preferences.

Example for Closest Proximity- On the next image (Figure 37) an OLIA tool at work on the previous layout organization of the café can be seen. While this layout is being analyzed, only visually manageable amounts of data is inserted.

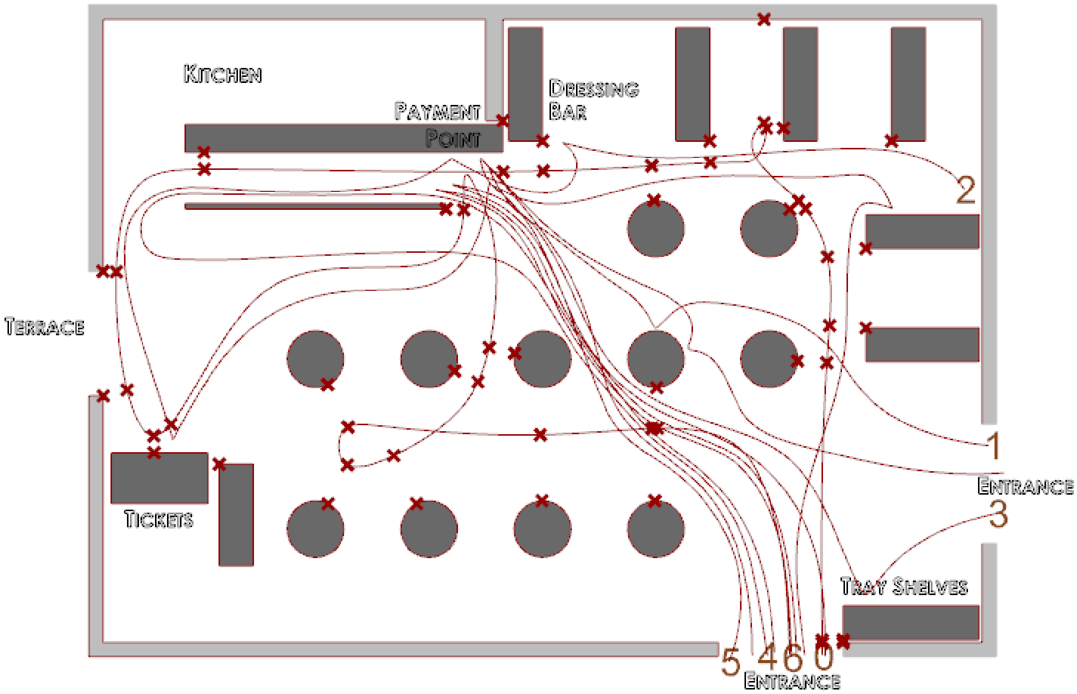


Figure 37. IEU Campus FFA Café- Spatial Layout and Occupant Trajectories analyzed with OLIA Tools

With this tool, analysis process yields quantity and distance information. Trajectories are counted and one trajectory is analyzed with *Closest Proximity* operation yielding a list of proximity data between a specific trajectory and other layout elements and/or trajectories. While OLIA outputs lists that can be processed in databases, it also has a visual aspect that provides users with images displaying the results of operations that run on layouts. Lists (Figure 38), on the other hand, work as input for TDPF for the process of layout evaluation and for providing responses for queries of users.

In this case, the values received from the *Closest Proximity* operation shows that occupants come close to each other and/or layout elements at a least distance of *21cm.* The coordinates where these instances happen are also listed.

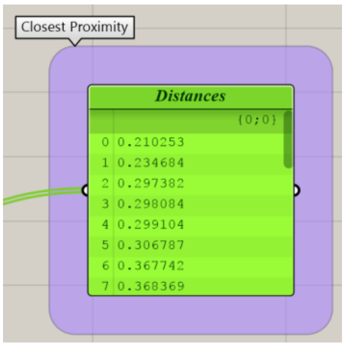


Figure 38. List showing closest proximity (21cm) and 25 other point distances for Closest Proximity

Example for Number of Occupants - To view and display occupant counts the operation called *Number of Occupants* is used on a grid of various resolutions that can be controlled with resolution sliders.

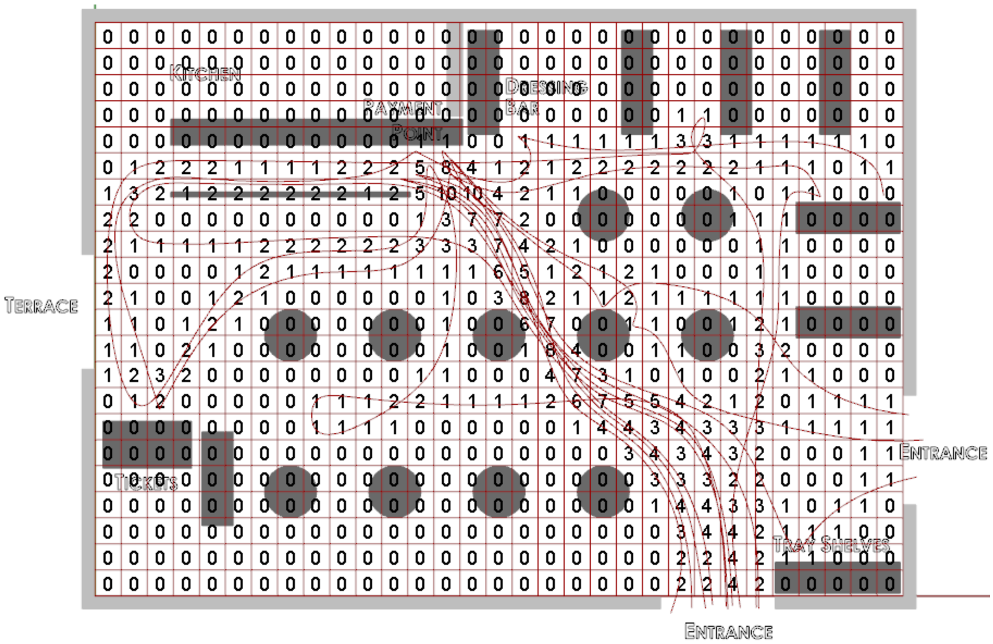


Figure 39**.** IEU Campus FFA Café before layout change- Counting number of occupants with OLIA at a resolution of 50 cm on occupant navigation layer

The seating layout of FFA Café, compared in OLIA with two different layout organizations (Figure 39-Figure 40) displays the changes and similarities in navigation patterns between two layouts. A pattern for viewing how many people uses which trajectories during which hours can be obtained for before and after the revision in layout organization.

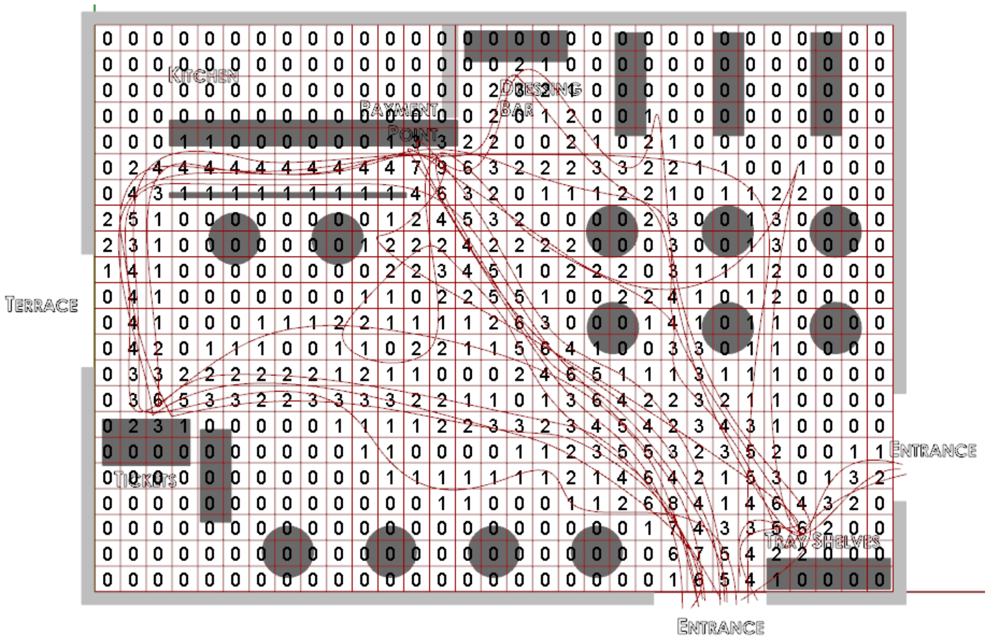


Figure 40. IEU Campus FFA Café- Counting number of occupants with OLIA at a resolution of 50 cm on occupant navigation layer

Example for Time and Speed - Timestamps however require further development for a precise tracking in all cases although OLIA has the necessary operations and tools to compute temporal and speed related analyses. Therefore, with the temporal data in hand, speed is computed in the new layout of the café. Users of OLIA can also view speed information both as lists and/or tags by using the operation called Speed.

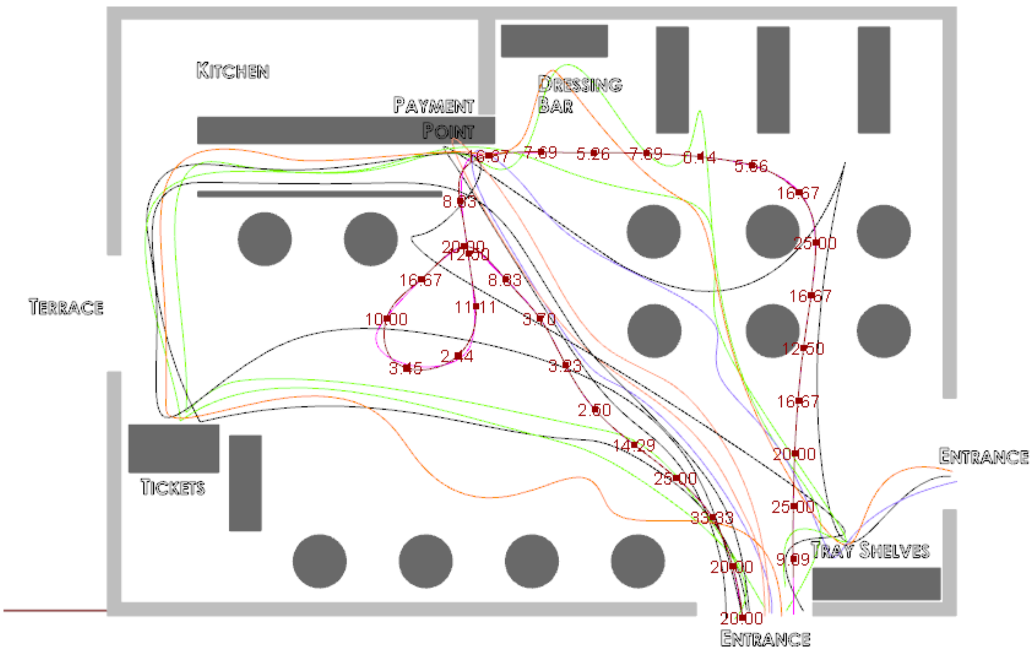


Figure 41. IEU Campus FFA Café - Determining Speed on each trajectory

This operation (Figure 41) gives output based on time and distance that are determined by the user in terms of units and recordings of their layout that is being analyzed. Speed at each point with temporal data is indicated on trajectories.

Example for Average of Trajectories - To manage complexity, the curves are averaged by using Average of Trajectories in OLIA. The average curve tool is run iteratively until all trajectories are averaged. Users have the option to pick trajectory curves of their own choice depending on where they specifically want to analyze. Here, OLIA computes and defines an average trajectory curve and checks for *closest proximity* points and distances. (Figure 42)

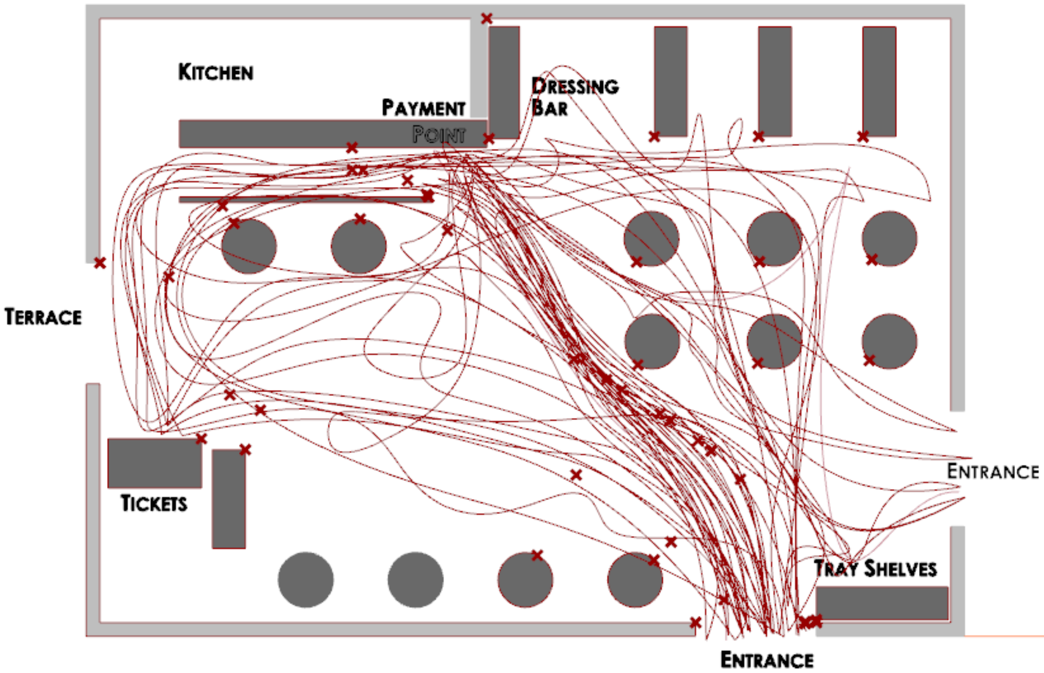


Figure 42. Trajectory analysis with the operation "Closest Proximity" of OLIA

The figure below (Figure 43) displays the resulting visual and numeric output in OLIA for counting occupants per zone at a resolution of 2.2m. That is the same resolution set for the image used in the questionnaire. This operation is fed with 60 trajectories recorded. The numbers within each zone display how many times each zone has been occupied for each trajectory recorded. It can be viewed from the graphic that although respondents of the questionnaire did not specify any layout issues in the central zone of the plan, there is an indication of an over-crowd as read within cells as, 88, 53, 62 and 106.

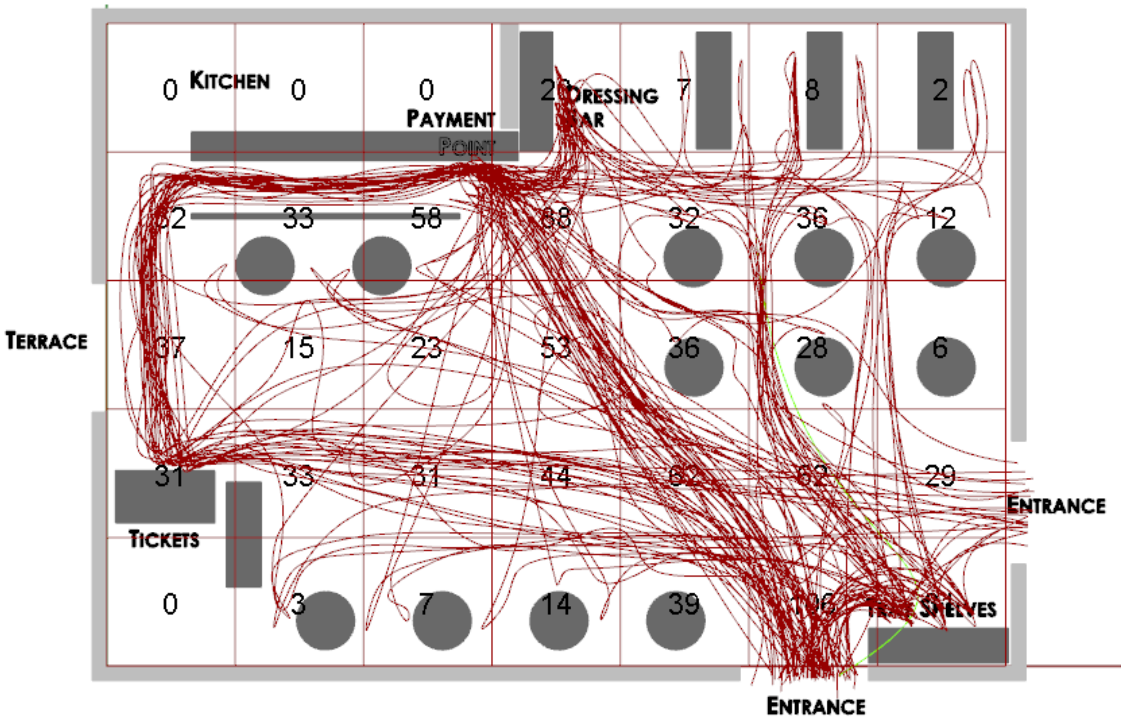


Figure 43. The operation for "Number of Occupants" called "Count Users" of OLIA is used to reveal zones that are most used- Resolution 2.2m

Next, is the same operation used to display dense areas at a resolution of 0.5m. A small number of trajectory curves are put in the operation for legibility purposes. While 18% of respondents expressed that they did experience insufficient clearance as one of the possible layout problems that can be encountered this layout problem was also tested with OLIA on this place. Therefore OLIA revealed a similar problem and displayed both numeric and visual information on where the zones in concern are. Coordinates and proximity levels are also revealed as lists within OLIA as shown in Figure 45.

5.4.4. Behavior Interpretation

Results of questionnaire are also compared with the outcomes of TDPF analysis for Case III. When occupants entered numbers based on their perception for over-crowded zones within the Café, their responses (Figure 34) revealed a pattern that is very close to what is revealed from an operation of OLIA as displayed in both Figure 43 and Figure 44. Although fairly similar visuals are obtained from three images (Figure 39, Figure 41, and Figure 43) OLIA's objective capability surpasses occupants' perceptive knowledge in terms of evaluating zones within the layout.

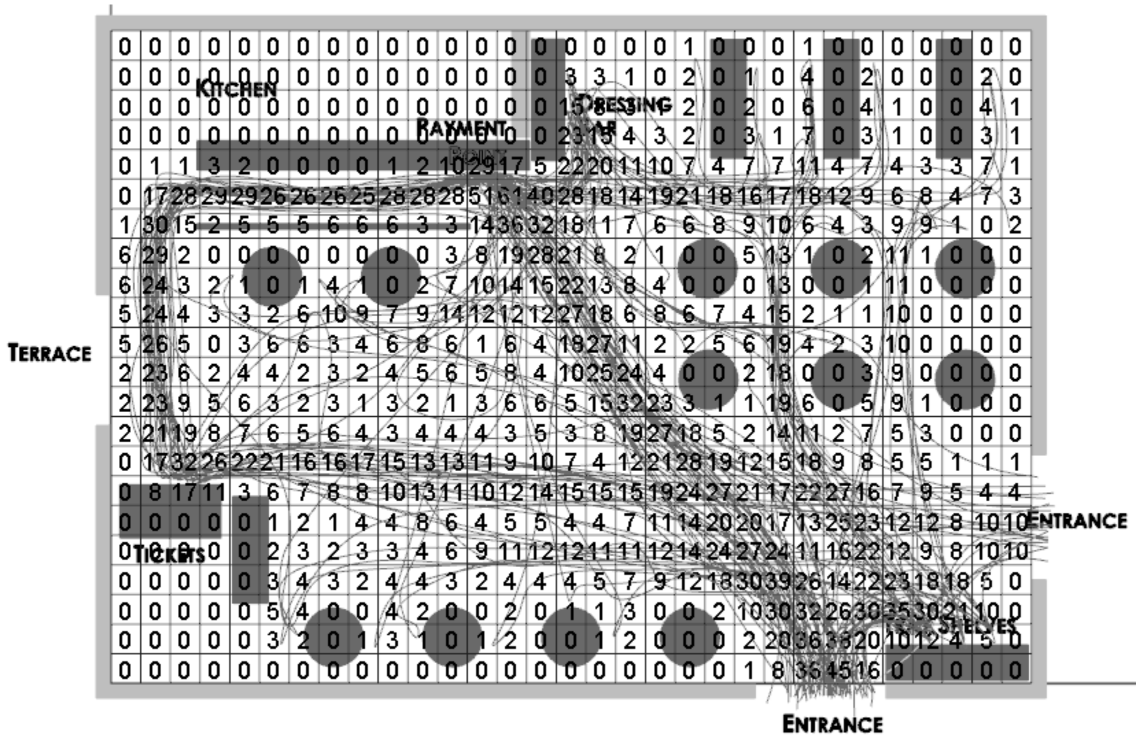


Figure 44. The operation for "Number of Occupants" called "Count Users" of OLIA is used to reveal zones that are most used- Resolution 0.5m

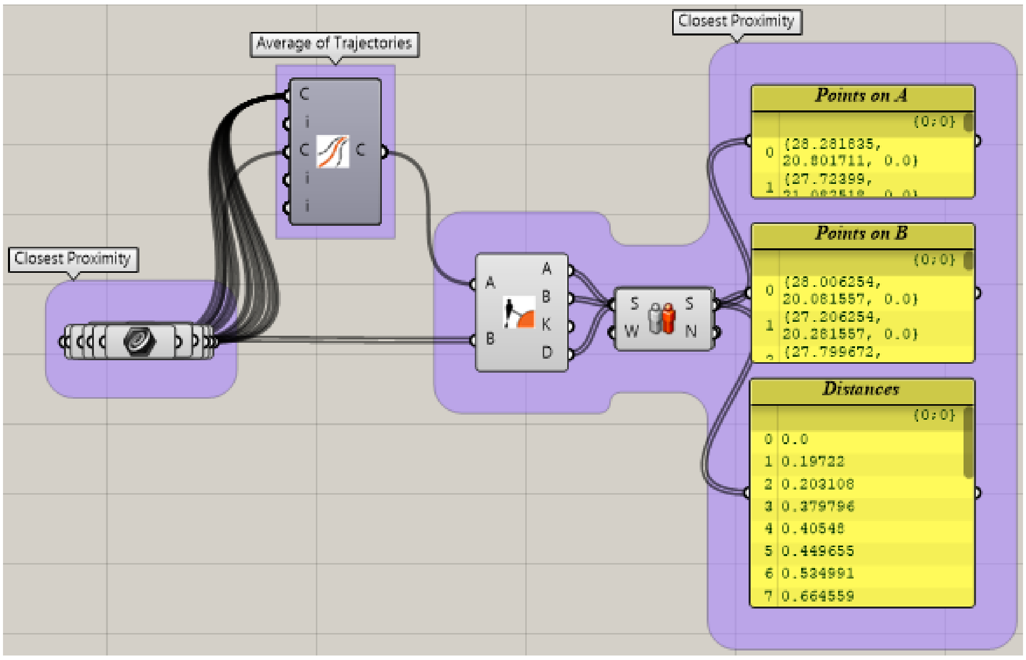


Figure 45. OLIA tools for Average of Trajectories and Closest Proximity

By analysis of speed here, *bottlenecks* and or *wayfinding* confusion patterns are observed and correlated to those layout problems. When speed is under a certain threshold that is set by the user, the yielded pattern provides insights for the user. *Insufficient* *clearance* within TDPF is correlated with *interrupted navigation* or *changes in pace* and with *closest proximity* levels with immediate surroundings.

5.4.5. Performance Evaluation

Since performance evaluation is based on values it is beyond the scope of these cases that are set to show OLIA in practice. However, as stated before, it is at users' discretion to set threshold values. These values are expected to emerge gradually as common levels, through accumulation of data in time.

5.5. Summary

OLIA analyses do verify the questionnaire results and/or expert assessments in various instances. However, there are and may be instances where they do not match. This is also valid since it is a presumed within this research that objective data and information based on subjective perception would yield complementary results rather than a juxtaposition.

The cases display that spatial layout analysis can be done by monitoring occupant layout interaction and comparing subjective and objective data as in cases I and III. Therefore, a methodology for quantitative evaluation of spatial layouts is operational although it needs further improvement that may take huge numbers of cases to accumulate and process data in order to serve as an expert system as seen in all three cases. Layers that space is pealed into for each case does help the research focus on capturing, analyzing and interpreting spatial layouts by fitting trajectory data into a framework to understand possible correlations with layout problems.

5.6. Improvements

Trajectory processing should be improved based on case analysis outcomes. For example one of the tools of OLIA as previously explained is Definition of Loop. While it is definitely needed to define what a loop is for TDPF, this very definition will gradually change and become a more elaborate tool for the framework through conglomeration of data.

OLIA runs currently on Rhino as a Grasshopper plugin set. However, it can also be converted to other scripting languages on other software as well as other visual programming environments such Dynamo etc.

CHAPTER 6

CONCLUSION

6.1. Contributions

Bridging the gap in understanding of spatial layout problems through an analysis of occupant interaction with spaces was the primary goal of this research. A research platform to facilitate quantitative evaluation of space layouts was intended. Quantitative analysis of spatial layouts is essential in evaluation of architectural spaces and standards development. Currently, the only quantities that are used by post-occupancy studies are distance measurements and area calculations. This dissertation first proposes an overall spatial layout evaluation methodology for quantitative analysis of occupant utilization of spaces. Following this methodology, it will be possible to identify when and where problems emerge in spaces and even set standards. For example, occupant densities in a cafeteria can be tracked in terms of number of occupants in a specific area during a time interval of interest. When the space becomes inadequate can be identified, thresholds can be set to decide when the space needs to be expanded – all based on *objective* data. The four steps of the evaluation methodology are: Data Acquisition, Trajectory Analysis, Behavior Interpretation and Performance Evaluation. The dissertation focuses on Trajectory Analysis stage and defines an extendable framework for first parsing collected data, then aggregating, organizing and processing it to open it up to interpretation and later evaluation. Behavior Interpretation and Performance Evaluation stages are left out of scope of this thesis. It is expected that by using the framework developed here, future work will focus on how to match patterns in trajectory data with actual human behavior, identify layout problems, and finally define performance criteria.

Architectural spaces are evaluated considering elements on four different layers: Occupants, Flexible Elements, Fixed Elements, and Environmental Context. The layer on which this research operates is the Occupant layer. How furniture is used or the distances to emergency exits, or the orientation of the building is beyond the scope of this study. In order to consider occupant utilization, a clear description of occupant movements is required. As a platform for this description, a computational framework is described.

Appropriate processing tools are also created to help numeric analysis, aggregation, and summary of occupants' interaction with layouts. The extendable framework defines what a trajectory is, a file format for data collection, and 13 operations on trajectories that can be used to explore an initial set of 7 common problems associated with spatial layouts.

The methodology and tools developed in this study illustrate that spatial layout evaluation which, today, mostly depends on tacit architectural knowledge, can benefit from development of quantitative analysis methods and criteria. For testing and verification purposes a proof-of-concept prototype implementation of the framework has been developed as a plug-in for Rhino/Grasshopper design environment. The plug-in, called OLIA, is the tool created here to carry out trajectory analysis for layouts and give quantifiable feedback to its users.

Thus, in summary, the dissertation makes the following contributions:

- Proposes a methodology for quantitative evaluation of spatial layouts based on occupant behavior.
- Introduces an extendable framework for analysis and interpretation of occupant layout interaction. This framework is considered as a foundation for building connections and correlations between trajectory analysis and spatial layout problems.
- Lays the groundwork for developing performance criteria for spatial layouts that can be used for evaluations based on objective data in research fields such as post occupancy evaluation or space syntax.

6.2. Future Work

Throughout this research, efforts were directed towards developing a research platform for quantitative evaluation of spatial layouts. Analyzing trajectories or a superior method that could replace it, can find its knowledge base in Trajectory Data Processing Framework (TDPF). Therefore spatial layout analysis for indoors needs many improvements and data to feed into future automated systems for layout evaluation. As stated earlier, alternative cases for analysis can be service spaces such as transportation hubs, office spaces, shopping malls, production facilities, hospitals, and educational buildings etc.

In its current state of development, OLIA allows occupant trajectories to be used in plan layout evaluation processes. Analysis results of objective data – trajectories - can be compared to subjective data obtained through questionnaires and help identify occupant preferences and needs as was illustrated with Case III. However, the quest which TDPF is initiating, will not be complete without the development of overall performance evaluation metrics – the *Layout Evaluation Scor*ing (LES). Reaching overall performance metrics requires developing evaluation criteria through studying causal relationships between spatial layout problems and occupant behavior. TDPF is intended to be a research platform to enable such future work.

Adoption of OLIA by users and their feedback is important for this research platform to develop the contextual ground for architectural layout evaluation. Some gradual refinements are expected for all tools and operations of OLIA as they are employed in spatial layout analysis processes by users.

TDPF deals with occupant behavior. Thus, it is mainly a post-occupancy tool. Yet this tool can be used throughout a building's lifecycle. Research into crowd simulations is promising new systems that when integrated with OLIA, can be used during the design phase to evaluate alternative layouts based on hypothetical, simulated trajectories. This capability can impact decision making processes in design cycle. Understanding occupant behavior can also be operational when linked with control systems using real-time data.

As *image recognition* and *computer vision* methods improve, methods for analysis, interpretation and evaluation of spatial layouts will gain more pace. Current developments in video based tracking of occupants are promising automated plotting of trajectories on plans for spatial layout evaluation. The fast accumulation and analysis of objective data may help build up databases of values, indices, scores and create libraries. These libraries may enable evaluation of layouts at early stages of design. Interpretation of occupant interaction with their environment can determine whether design intentions are met or not and appropriate solution strategies can be developed for identified problems.

Quantifying, that is translating experiential/tacit knowledge into datasets, relations, actions, operations, values, raises the scalability of systems. When an action or any element of a process is quantified, it becomes more suitable for speeding up, learning and/or repeating, that is automation. In the long term, once quantitative evaluation of layout performance is established, even a possibility of automated spatial layout generation and evaluation and the issue of architectural production without the architect in the equation can be investigated.

When machines design buildings, it will probably be the time for *architect-less-ness*. However, there will definitely be something or someone that will be *the new kind of an architect.* Although it will be an environment without an architect as we know it, there will definitely be human nuances in the process. Enabling analysis and interpretation of how occupants interact with space and hence opening the door to quantitative evaluation of spatial quality is a step towards improving the built environment not eliminating the human designer from the design process.

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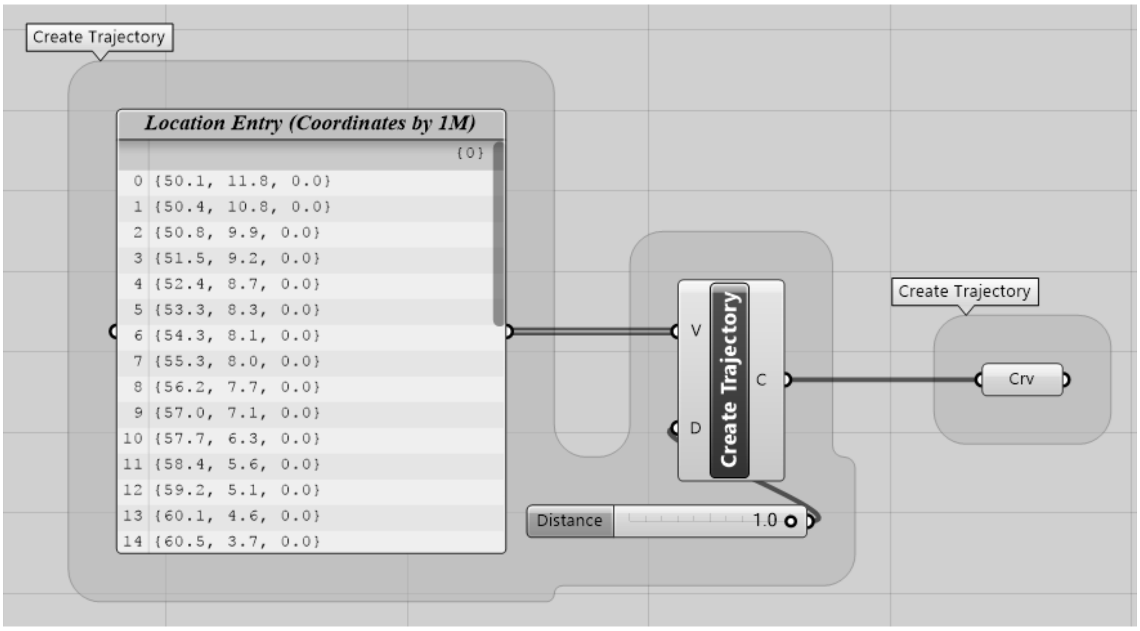
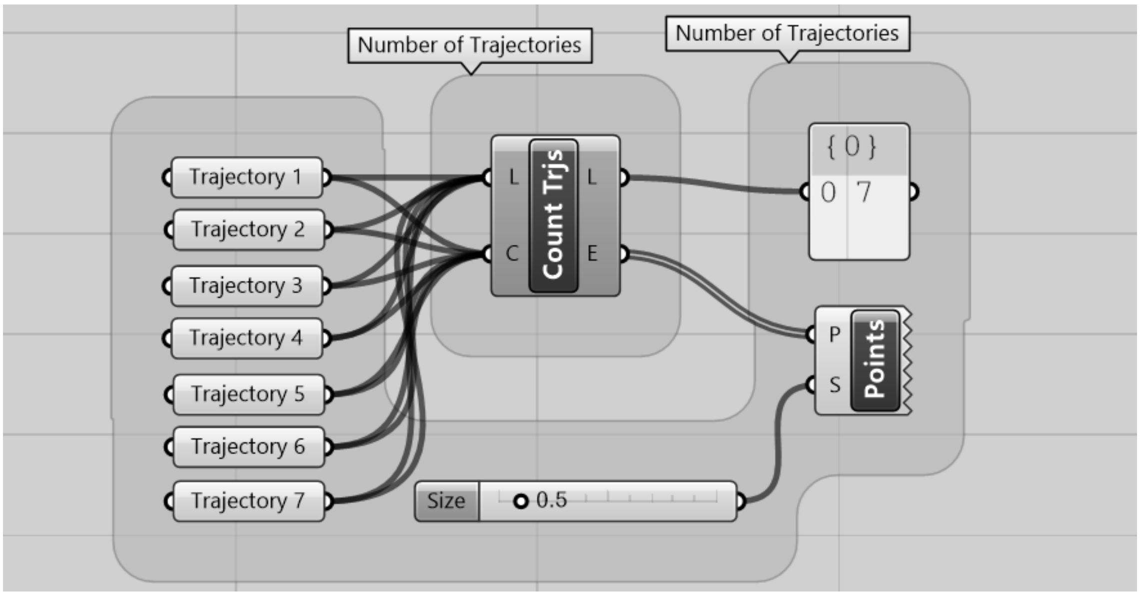
APPENDIX A

OLIA TOOLS AND OPERATIONS

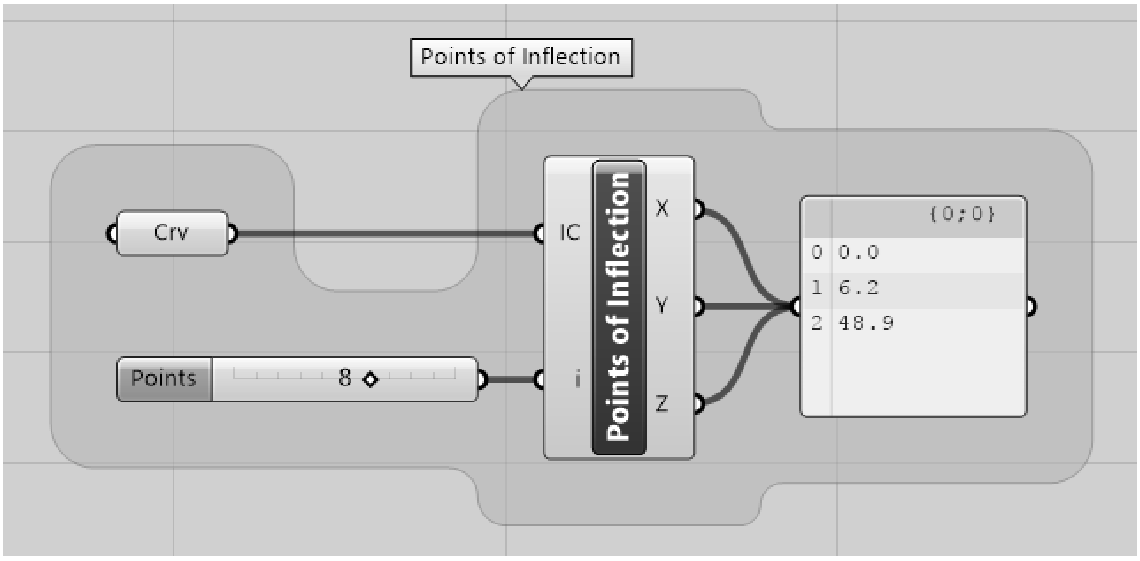
1 Create Trajectory



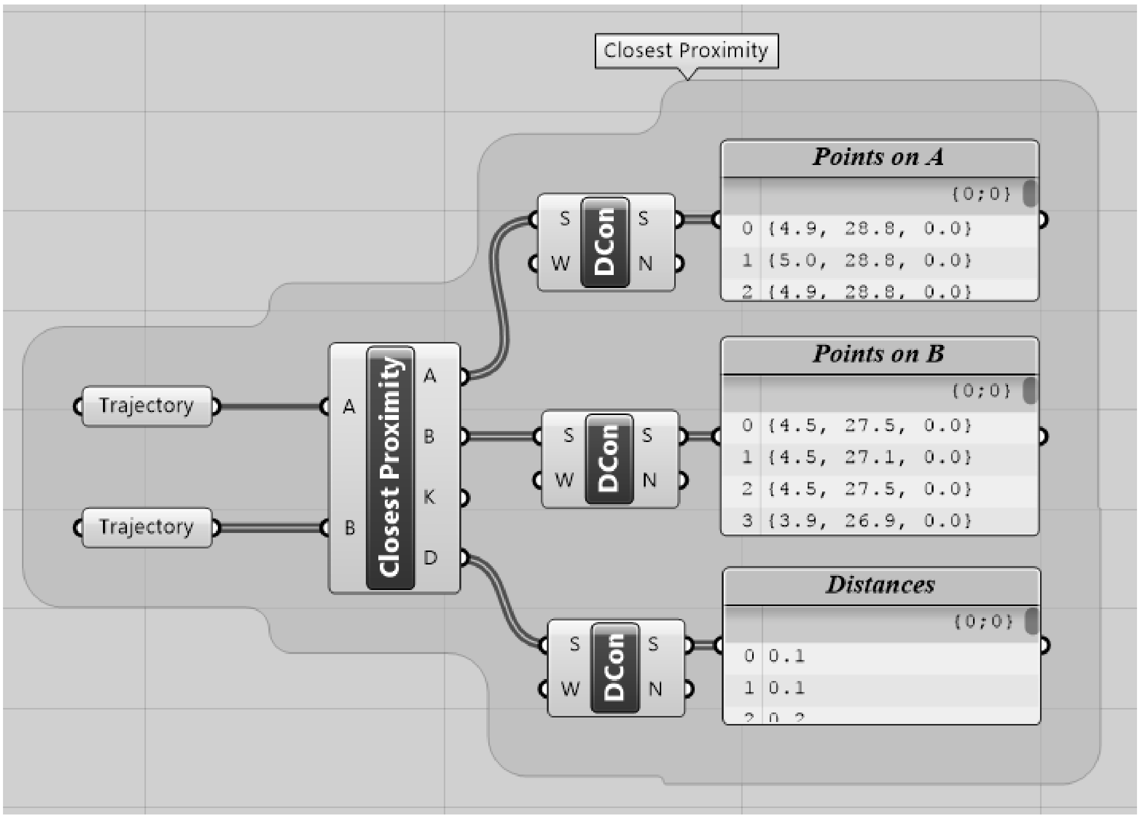
2 Number of Trajectories



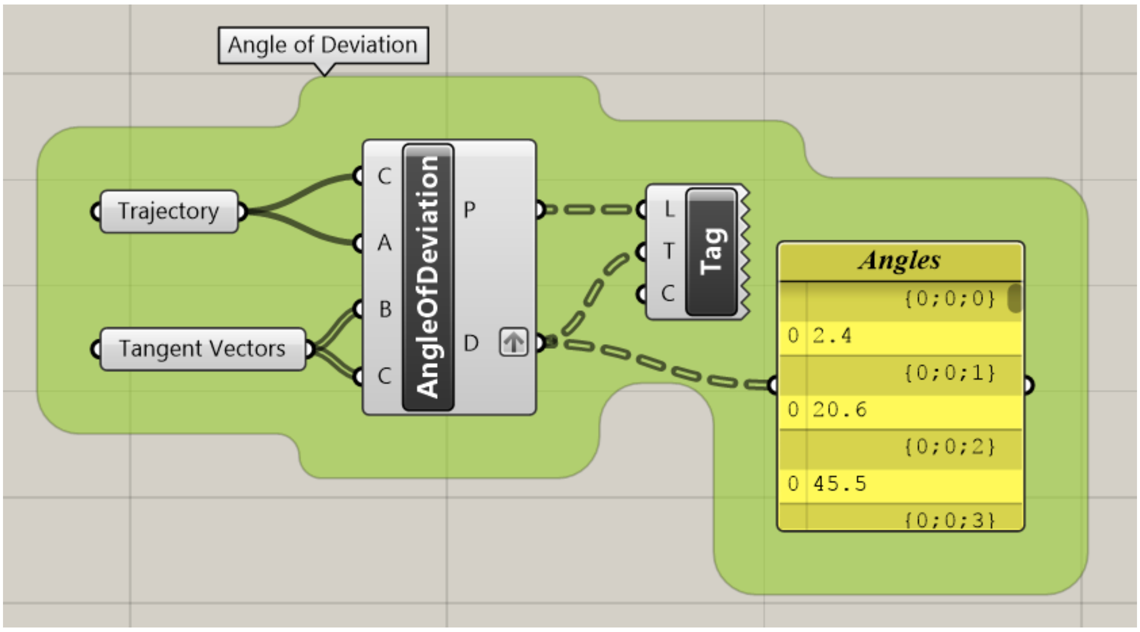
3 Points of Inflection



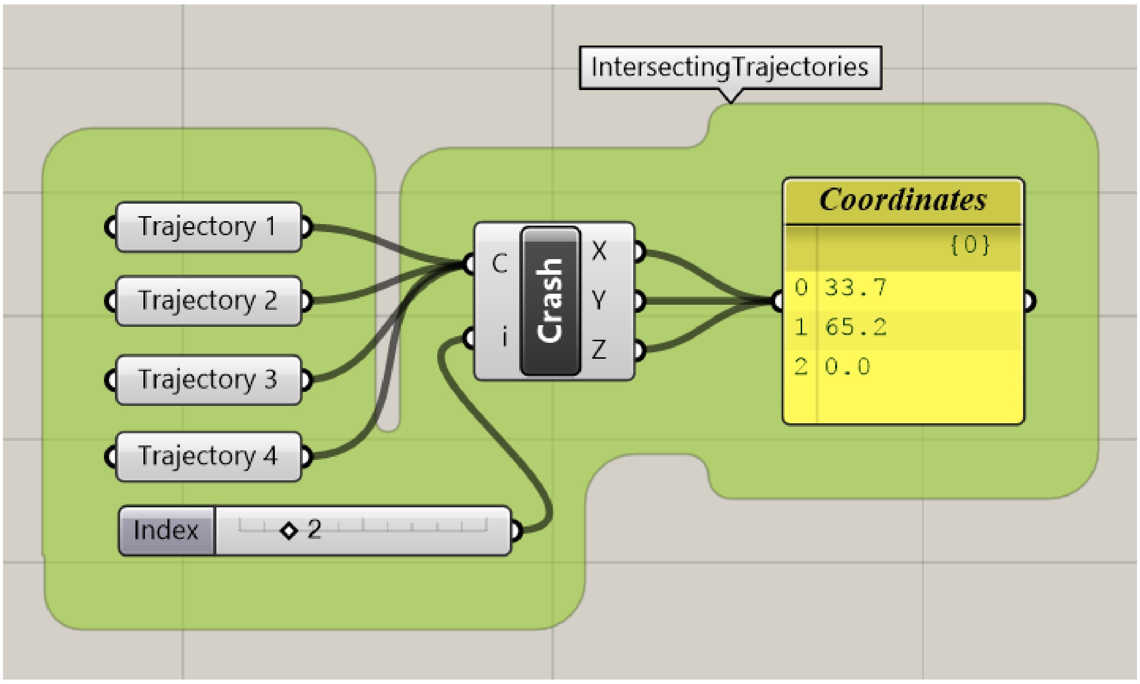
4 Closest Proximity



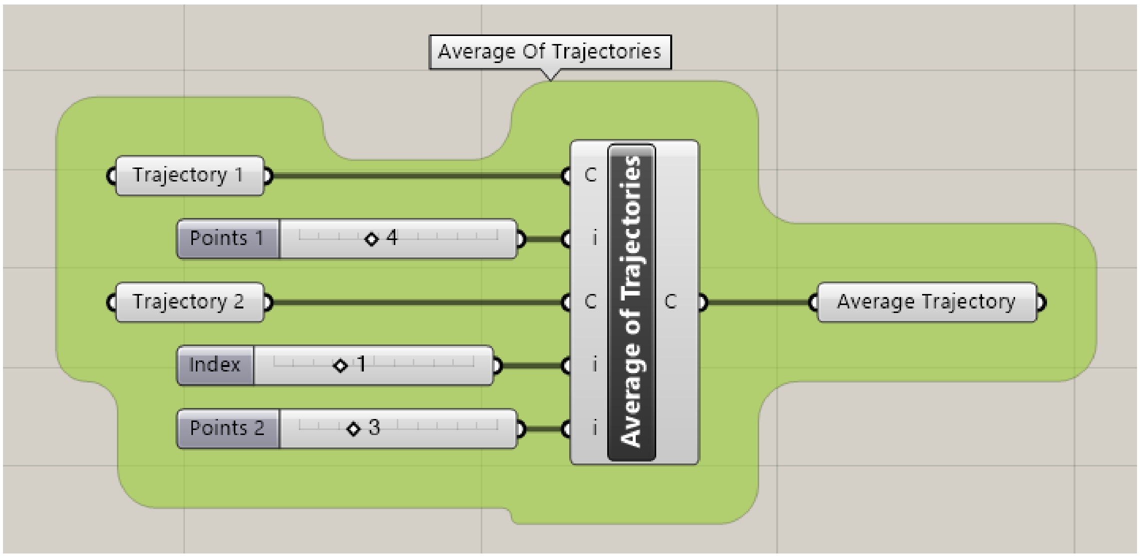
5 Angle of Deviation



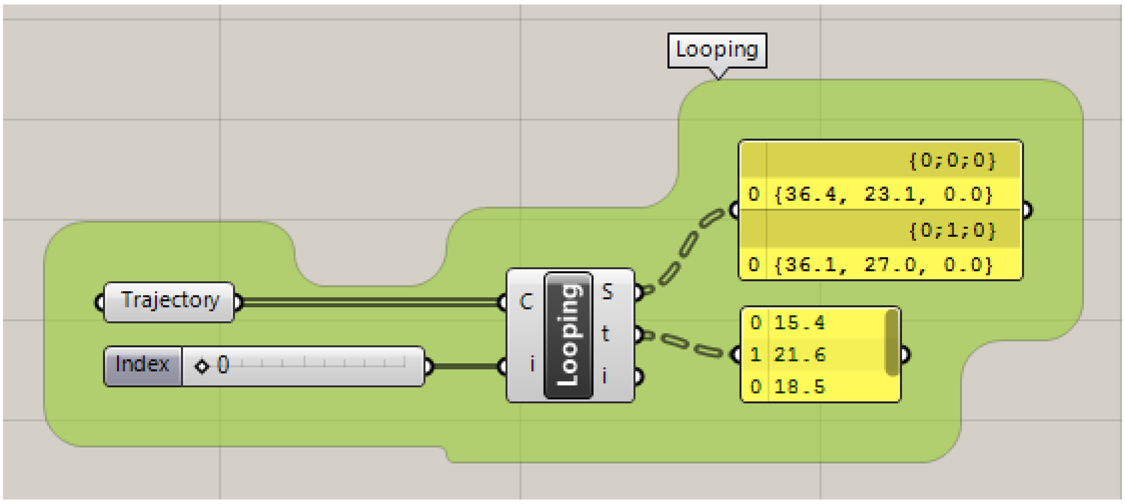
6 Intersecting Trajectory Lines



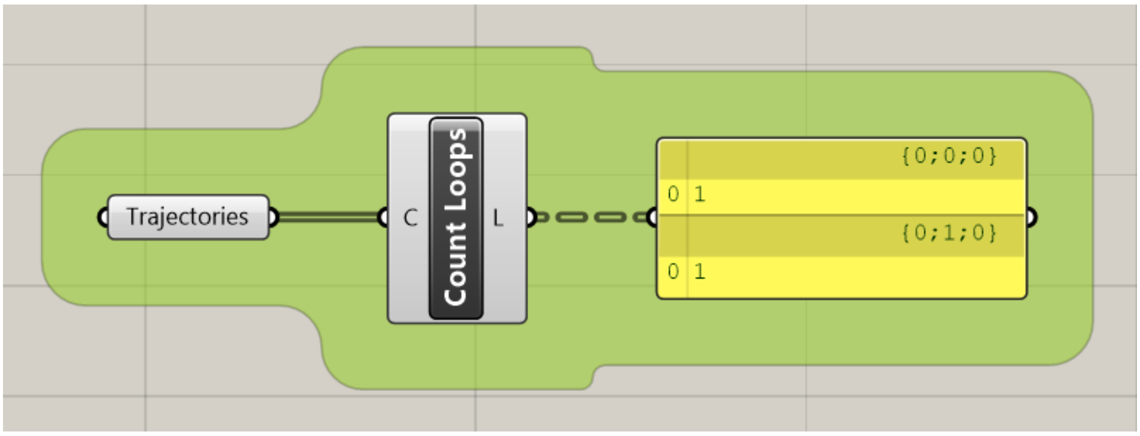
7 Average of Trajectories



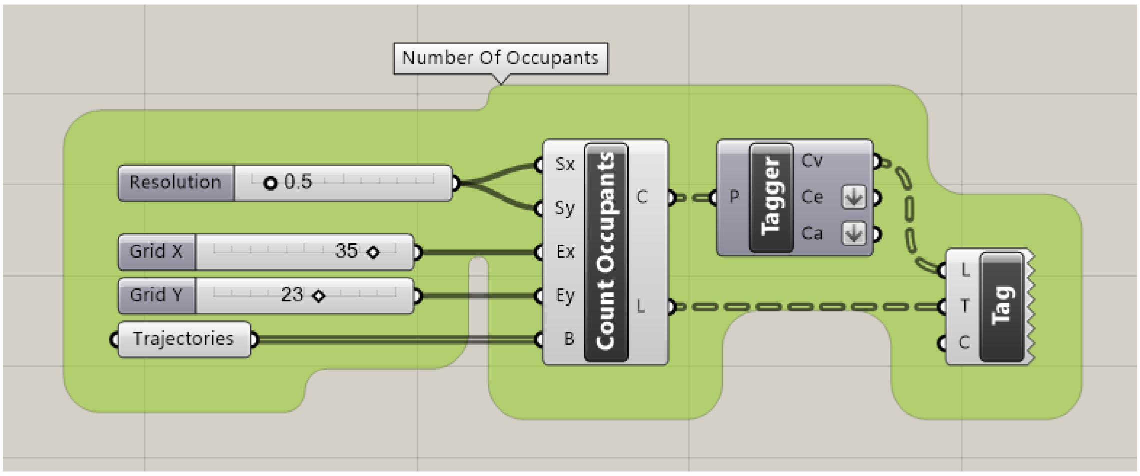
8 Definition of Loop



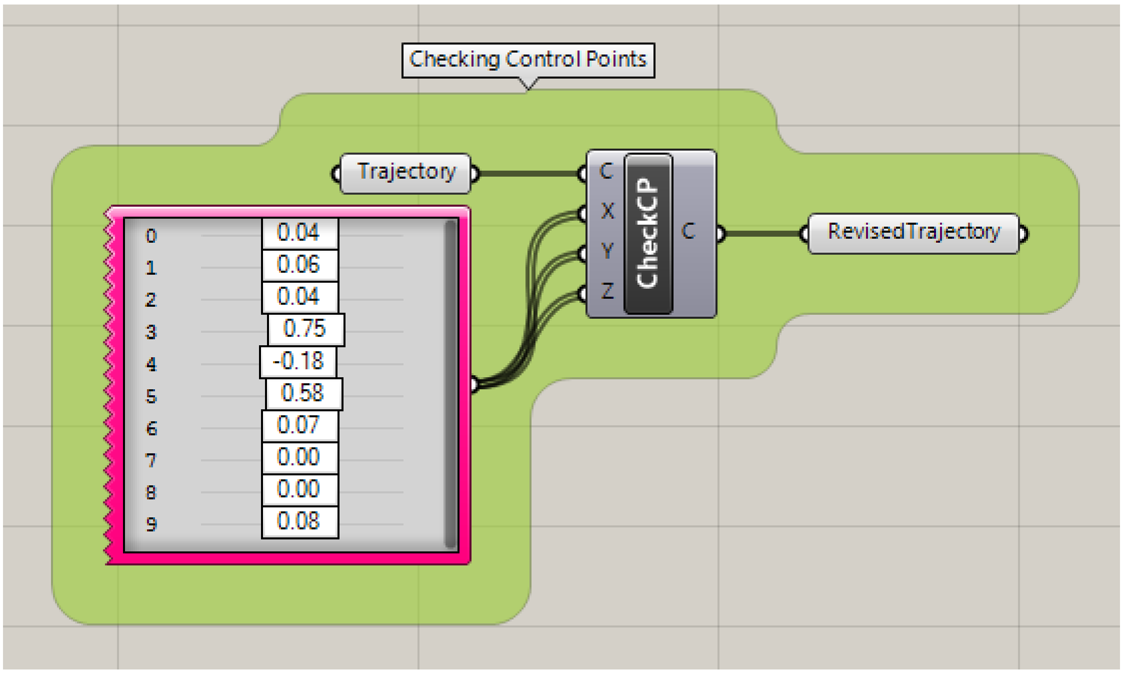
9 Number of Loops



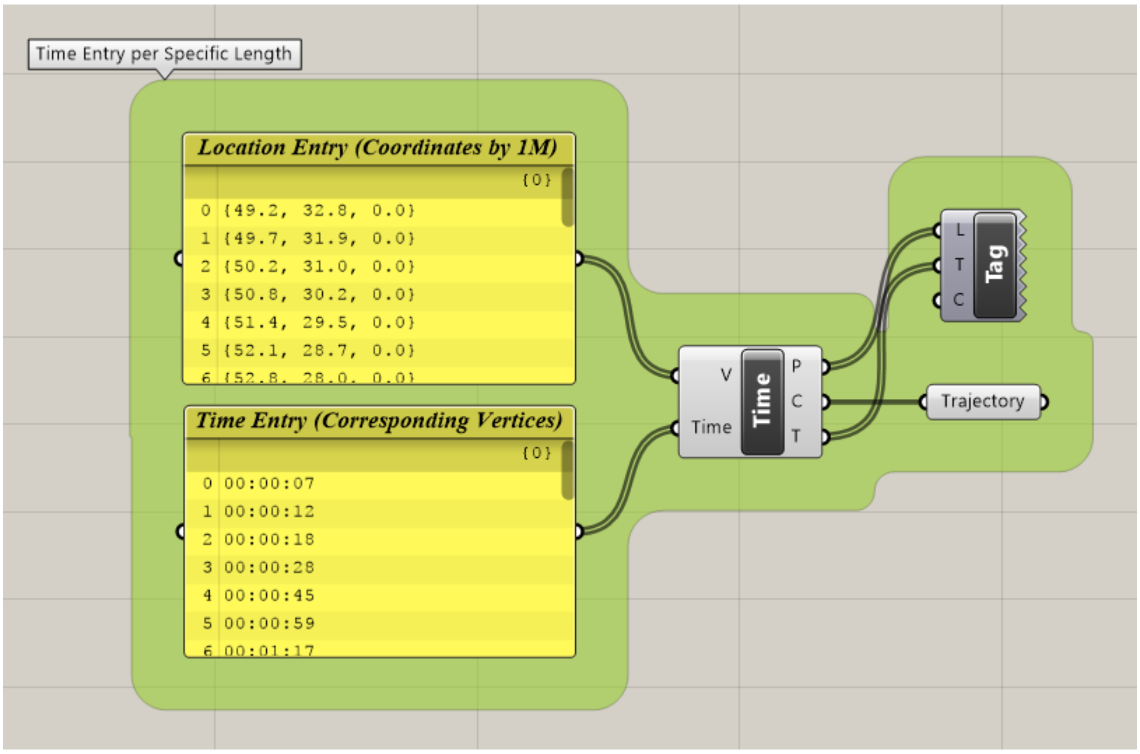
10 Number of Occupants



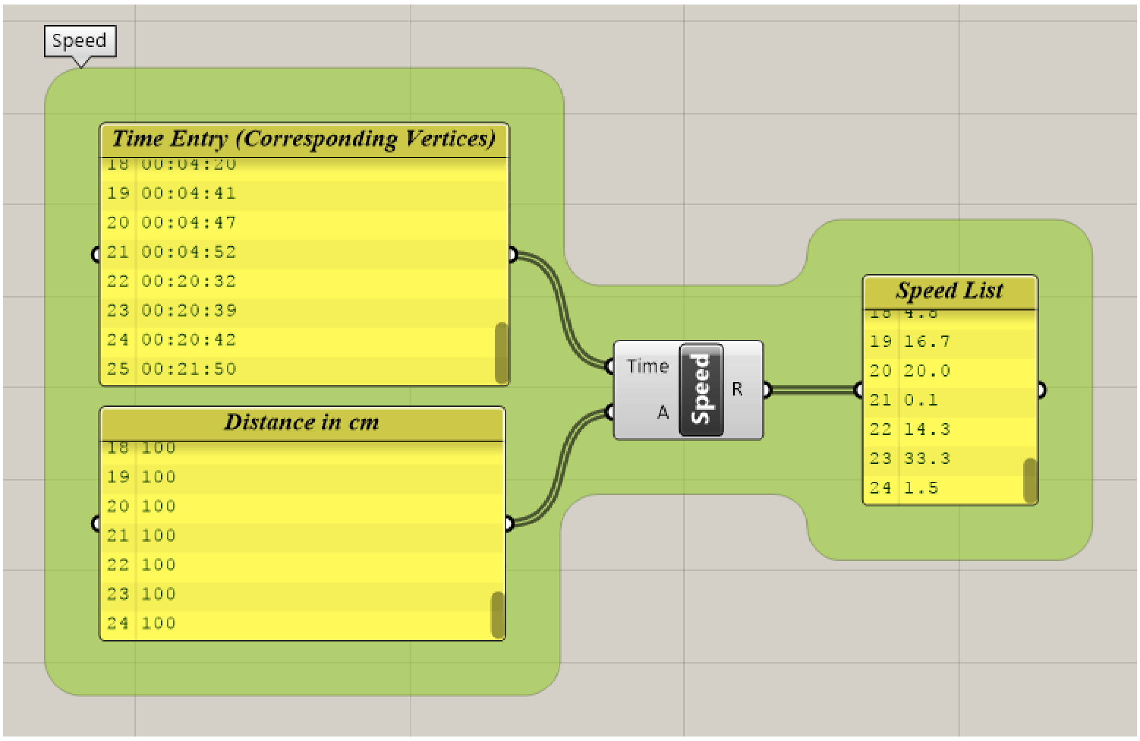
11 Checking Control Points



12 Time Data Entry



13 Speed



APPENDIX B

QUESTIONNAIRE

IUE / Fine Arts - Café

Questionnaire for Customers - Spatial Layout Evaluation

* Required

1. **1. How frequently do you visit this Café? ***

   Mark only one oval.

   - ⬭ Never *After the last question in this section, stop filling out this form.*
   - ⬭ Once or Twice a week *After the last question in this section, skip to question 5.*
   - ⬭ Everyday *After the last question in this section, skip to question 5.*
   - ⬭ I do not use this space. I only walk through it.

2. **2. Name and Last Name (Optional)**

   ____

3. **3. Department (Optional)**

   ____

4. **4. When do you mostly visit this Café? (Please check all that applies)**

   Check all that apply.

   - ☐ 08:30 - 11.30
   - ☐ 11:30 - 12:30
   - ☐ 12:30 - 13:30
   - ☐ 13:30 - 16:00
   - ☐ 16:00 - 18:00
   - ☐ All

Evaluating IUE / Fine Arts - Café for Layout Problems

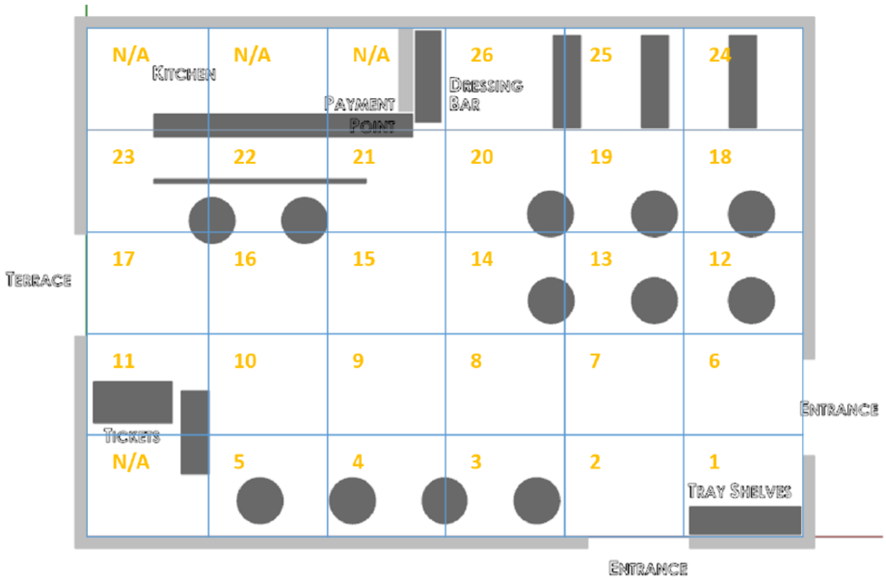
Questionnaire for Occupants - Spatial Layout Evaluation

5. **5. Do you see the following layout problems in this place?(Please check all that applies)**

   Check all that apply.

   - ☐ Over-crowded Space
   - ☐ Wasted Space
   - ☐ Clutter, indirect access
   - ☐ Bottlenecks
   - ☐ Inefficient Wayfinding
   - ☐ Unpredictable Usage / Unexpected crowd in certain zones
   - ☐ Insufficient clearance
   - ☐ I am not sure
   - ☐ I don't see any problem

Zones for IUE / Fine Arts - Café Plan Layout



6. **6. Due to the layout, customers accumulate at certain zones (Please add the Zone Numbers below)**
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

7. **Zone Numbers**

   ____

8. **7. I try to avoid certain areas in this place.(Please add the Zone Numbers below)**
   Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

9. **Zone Numbers**

   ____

10. **8. I see wasted space zones in this place.(Please add the Zone Numbers below)**
    Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

11. **Zone Numbers**

____

12. **9. I experience bottlenecks in this place.(Please add the Zone Numbers below)**
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

13. **Zone Numbers**

____

14. **10. From time to time, I notice unpredictable usage/ unexpected crowd in certain zones. (Please add the Zone Numbers below)**
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

15. **Zone Numbers**

____

16. **11. I can access certain points(parts) smoothly eg. the counter, any seating, ticket vendor or tray shelves etc.**
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

17. **12. It is easy to find my way around in here.**
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

18. **13. This place has an overall good spatial quality.**
Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

VITA

Lâle Başarır was born in Ankara, in 1971. She received her BArch degree in Architecture from Gazi University in 1994. She studied Industrial Design as a second degree at CCAC (now CC&A) and received her MSc degree from Architectural Design Computing program at ITU. She completed the inaugural GSP-09 class at Singularity University at NASA Ames Research Center in 2009. She graduated from Izmir Institute of Technology with a PhD degree in Architecture in 2018.

Lâle has worked as an Architect, an Industrial Designer and as a Jewelry Designer since 1993. In 2001, she established The Glass Furnace educational and artistic programs and consecutively worked as the Director of Arts & Education until the end of 2003. She founded Su Düşleri Architecture and Industrial Design Consultancy in 2006, in Istanbul. She has been a part-time lecturer at İzmir University of Economics and İzmir Yaşar University since 2011.