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Occupant trajectory analysis for evaluating spatial layouts

Lâle BAŞARIR[1], Mustafa Emre İLAL[2]
[1] academylaleb@gmail.com • Department of Architecture, Faculty of Fine Arts, Izmir University of Economics, Izmir, Turkey
[2] emreilal@iyte.edu.tr • Department of Architecture, Faculty of Architecture, Izmir Institute of Technology, Izmir, Turkey

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Abstract

Comparing architectural designs as well as measuring their level of success is a challenging task. Tracking of occupant movements provides objective data facilitating the development of new metrics for evaluating spatial layouts. This paper starts by outlining an overall methodology for Spatial Layout Evaluation based on occupant movements. Then, a platform for acquisition and interpretation of objective data to better understand how space is utilized by occupants is introduced. This platform is the Trajectory Data Processing Framework (TDPF). It supports investigating correlations between occupant movements and problems associated with spatial layouts. Finally, as a proof-of-concept implementation of this framework, a set of tools for analysis of occupant interaction with layouts, called Occupant Layout Interaction Analysis (OLIA), is presented.

Keywords
Building performance, Spatial layout evaluation, Occupant tracking, Trajectory data processing, Layout problems.

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1. Introduction

The tacit nature of knowledge (Woo, Clayton, Johnson, Flores, & Ellis, 2004) utilized in design makes comparing designs and measuring level of success rather difficult. Architectural practice does not emphasize juxtaposition of design intent with the resulting plan layout to fit occupants' needs. In order to measure design success a quantifiable evaluation method is needed.

Building performance research has determined many quantifiable criteria (thermal, lighting, energy efficiency, etc.) along with multitudes of simulation tools to support the design process. Furthermore, 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. Unfortunately, architectural layouts cannot be evaluated in the same manner. There is a lack of objective measures for evaluating plan layouts (Leaman, Stevenson, & Bordass, 2010). Quantitative plan layout evaluation, is still severely limited. 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). Even though there is significant research on design thinking which Oxman (1999, 2008) provides a good summary of, 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 behaviour, there comes a possibility to uncover the implicit knowledge that reflects itself in behavioural clues.

Lack of occupant behaviour tracking and its understanding in terms of spatial layout problems constitutes the gap that underpins the major motivation for this research. 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' overall interaction with layouts is required.

The current article presents such a research infrastructure. Its main objective is to guide the development of automated data collection systems as well as provide future research with the necessary tools to interpret occupant behaviour for both identifying layout problems and developing performance criteria for layout design. Current scope is limited to consolidation and analysis of occupant movement data. It does not extend into behaviour interpretation. Investigating relationships between objective data on movement and observation data on behaviour is left for future studies.

2. Background

Within this research, occupant behaviour is considered as a data source for evaluation of architectural space. Liggett classifies spatial layouts based on underlying problems that form them: *Space as discrete objects*, *Space as area* and *Space as area and shape* (Liggett, 2000). 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 provide the basis for the geometric level. Geometrical level is set for dimensioning of spatial designs using optimization techniques based on multiple criteria (Jo & Gero, 1998). This classification of topological and geometric levels draws a comprehensive frame for both generation and evaluation of spatial layouts. However the occupant movement within that space and objective measures for identifying the occupant experience are yet to be discovered. Spatial layout evaluation is done at topological and geometric levels without the users that occupy the space.

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* (Hillier et al., 1996). 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 developing ways to convert spaces into topological relationships. 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). 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.

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). Space syntax research employs both automated and manual collection of data with two methods: Gate counts and following the path of visitors. 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 (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*. Space Syntax methodology is introduced through open source platform and uses its dedicated software. The software is called Depthmap and is based on the space representation and analysis method of Space Syntax (Al-Sayed, 2014).

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 rapidly improving. Video processing systems that track pedestrians are being developed (Dehghan et al., 2014). A review of the pedestrian detection and tracking studies within computer vision research is provided by Brunetti et al. (2018). Yet, none has been employed for spatial layout evaluation. Problems with layouts are being analysed within the scope of efficiency in production or commercial spaces, and metrics such as visibility, accessibility, and attraction are utilized (Wineman & Peponis, 2010). There are several applications and models for both design and evaluation of spatial layouts. For example, the following three models display layout analysis models that are used for hypermarkets (Inglay, Park, & Andheri, 2010): 1. Mathematical Programming Models facilitating optimization for criteria such as *space efficiency, distance travelled, service convenience* etc. 2. Queuing Models providing feedback based on *queuing situations* at the elevators, service desks, parking etc. 3. Simulation Model providing a selection of experiments to rate among various criteria. Similar research provide several options for defining criteria that can also be employed within evaluation of layouts besides generation of layouts. However, although these models contain analyses such as *Customer Flow* and *Activity Relationship* defining customer behaviour they do not base their research on tracking and interpretation of occupant movements. Therefore, criteria that are used in simulations form a rich repository for spatial layout evaluation. A research on planning an evacuation system based on simulation, proposes an evaluation system for office layouts with evaluation criteria of *impassable spaces, crowded areas, other agent's actions* etc. 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 behaviour than agent decisions within simulation environments, simulations carry valuable knowledge referring to occupant behaviour and evaluation criteria. 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 behaviour, especially in urban environment is perceived by Golledge (1992) 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.

Observing the way people navigate Conroy (2001) came to the conclusion that people pick straight lines for reaching their destinations. 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 behaviour and the effects of their environment.

Building Performance Evaluation (BPE) provides feedback on various aspects of space use. Preiser and Vischer (Preiser & Vischer, 2005) define BPE as a feedback system to maintain building quality throughout the design, construction, occupation and operation phases. BPE studies focus on user satisfaction and *Post-Occupancy Performance Evaluation* (POE) is an important tool to understand how users interact with buildings. POE tries to answer four broad questions: *'how is this building working?', 'is it intended?', 'how can it be improved?',* and *'how can future buildings be improved?'*(Leaman, Stevenson, & Bordass, 2010). Buildings are evaluated under six headings: *Thermal, acoustical* and *visual environments; spatial quality; air quality,* and *building integrity* (Hartkopf & Loftness, 1999). Architectural layouts are examined under building integrity but objective measures are limited to door-to-door distances and adjacency relationships between spaces.

3. Aim and scope

As stated earlier this paper presents a research infrastructure for qualitative evaluation of occupant movements within spatial layouts. For this purpose, a *methodology* to analyse occupant navigation within spatial layouts is described (Spatial Layout Evaluation Methodology); a *framework* that holds a structure for exploring links between occupant behaviour and evaluation of space is defined (Trajectory Data Processing Framework); and a *proof-of-concept implementation* of the framework named Occupant Layout Interaction Analysis (OLIA) is developed as a plugin for Grasshopper/Rhino platform.

The specific problems and indica-

Table 1. *Examples of Trajectory Data Interpretation.*

Indication in Trajectory Data	Observed Occupant Behaviour
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

tions this research deals with are not limited to the efficiency of space but are more importantly related with the *quality of occupant experience* extracted from *occupant navigation* through space. Table 1 lists indications in occupant trajectory data and their corresponding actual behaviour patterns, covered by the scope of this research. Depending on context and typology, these may be desired or undesired effects of the layout. Also, more than one behaviour pattern may be linked with indications in trajectory data.

The elements of a spatial layout that affect occupant navigation can be classified into four layers [Figure 1].

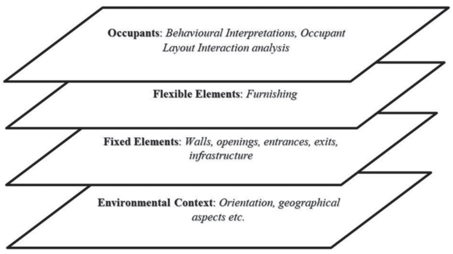


Figure 1. *Layers of Spatial Layout Evaluation.*

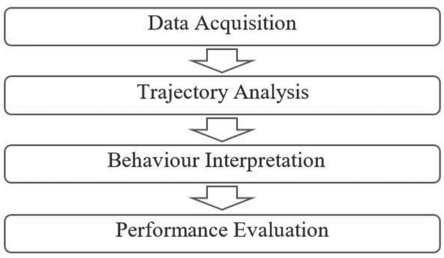


Figure 2. *Spatial Layout Evaluation Methodology.*

The lowest layer is related with environmental context that includes orientation and geographical aspects etc. Second layer is the fixed elements layer and it includes 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. Occupants that utilize space is considered as a layer of that space. The focus of this research is limited to the occupant layer.

4. Spatial layout evaluation methodology

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 based on occupant movement is a process that follows four steps [Figure 2]: Data acquisition, Trajectory analysis, Behaviour interpretation, and Performance Evaluation:.

4.1. Data acquisition

Capturing objective data on occupant movements is done by tracking occupants on two-dimensional (2D) plan layouts. This can be manual or automated using radio frequency tags or video processing. Regardless of the method of data collection, the core focus for data acquisition for spatial layout evaluation methodology purposes is to obtain the traces of occupants in the form of trajectories. Occupants are recorded as dots at their centres and turn into trajectories as they move in space. These dots define trajectories as defined by Zheng (2015). A spatial trajectory is a trace consisting of points recorded in terms of coordinate sets and timestamp e.g. p= (x, y, t).

Collecting objective data on space utilization can be difficult. For example, video surveillance is not appropriate for many spaces. In some spaces, even manual tracking through observation is not allowed. Yet, in most public spaces video surveillance is already installed and takes place. As video processing techniques improve, methods for acquiring trajectory data without raising privacy concerns and compliant with relevant legislation needs to be developed. Of course, it should be noted that no matter how advanced occupant sensing technology becomes, there will always be spaces where such surveillance will not be appropriate. In this research, data has been collected manually through observation of occupants with the help of video recording when available.

As we move through a space, while our bodies move in one direction, our heads turn towards various directions, and we may be moving sideways. Occupants as they move create a trajectory, but movements such as head and/or body rotation is currently not considered but future research looking into behaviour interpretation will certainly look into handling of such data. Similarly, movement in z-axis is left out of scope, but is included in the proof-of-concept implementation for future applications.

4.2. Trajectory analysis

Analysis of trajectory data is the second step in Spatial Layout Evaluation Methodology and is the main focus of the current research. Trajectory data collected needs to be analysed spatially and temporally before occupant behaviour can be interpreted. Quantitative analysis on trajectories provides objective metrics that behaviour interpretation will be based on. Trajectory Data Processing Framework (TDPF) is developed for this purpose. Its proof-of-concept implementation as a plugin for the Rhino/Grasshopper platform will be detailed in the next section.

TDPF facilitates semantic translation of raw occupant movement data acquired through observation, to quantified performance parameters through queries and calculations. The framework is structured to support the analysis step of the methodology but also defines a file format to be used in the data acquisition step and provides the necessary reports that will be used in the interpretation stage, bridging the first three stages of the methodology.

A Trajectory Data File (TDF) is a simple spreadsheet file. It uses the .csv and/or .xlsx format. This spreadsheet 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. The format is valid whether data acquisition is manual or automated.

Once the trajectories are received, they are ready for various queries that may be of interest. Possible queries that can be directed have been analysed as a first step for developing the TDPF. Table 2 lists some of the various queries that are supported by the framework. Queries are classified in terms of how they process trajectory data (operations) and what they produce as a result (output). The output data type cur-

Table 2. *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°?	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

rently are counts, coordinates, zones, time intervals, and booleans.

The quantitative data that is processed will support the development of metrics for use in behaviour interpretation and performance evaluation steps of the methodology. Various criteria, along with their units of measure and constraints can be determined. Density, Angles, Proximity of user to closest edges, Intersecting trajectory lines, Angles of deviation, Number of loops are examples of criteria. They utilize units such as Number of Users /area / time (optional), distance, degrees, or frequency. Constraints can be set as needed to determine threshold values for the relevant criteria.

4.3. Behaviour interpretation

Spatial Layout Methodology clearly separates numeric analysis from behavioural interpretation due to the complex nature of movement data. It is not easy to reason *why* someone moved in a particular way by only analysing *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, Wachowicz, Nanni, & Renso, 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. Priority should be given to understanding how trajectory data should be processed. Therefore, a framework is structured for organization of data.

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

Interpretation of behaviour on the other hand is explained under the title *possible influencing factors* for the observed occupant behaviour. Possible influencing factors are either related to spatial layout problems or not.

There is little available information and explicit knowledge base concerning underlying reasons for observed occupant behaviour of occupants. There is a gap in literature on identifying and understanding behaviour and relating them to layout problems. This gap is the main motivation for the Trajectory Data Processing 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 behaviour as proof for layout problems but merely to provide the necessary analysis tools for other researchers to further the 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. The set of identified layout problems is listed with corresponding indications in objective data and occupant behaviour in Table 3 and explained below:

- Over-crowded Space: One of the major concerns is that some zones are disproportionately more crowded than others within a certain space. 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. *Density* is defined as *number of people* per specified area.
- Wasted Space: Has earlier been defined as "the area of the building boundary minus the total area used as living space." (Michalek, Choudhary, & Papalambros, 2002) Therefore, a case of *no sign of occupancy* in a zone can be an indication of wasted space unless that zone serves another purpose that is not readable from the plan layout.
- *Clutter*, indirect access: Clutter, in-

direct 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.*

- Insufficient clearance: 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*.
- Bottlenecks: Spatial layout design dictates routes for inhabitants. Within these routes constrictions occur depending on use of space. Bottlenecks are seen and interpreted as o*verlapping routes* (trajectories) and evaluated based on *frequency per hour.*
- No alternative / better passage assigned: 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 a certain degree it is assumed that it is a transiting behaviour. This behaviour signals the possibility of absence of a passage for occupant who do not need to go through or stay in this place.
- Inefficient Way-finding: Wayfinding can be intuitive or inefficient. Appropriate layout design could provide intuitive wayfinding for occupants. When inefficient wayfinding is the case, occupants are observed with a typical behaviour; *wandering* as *if looking for something rather than heading towards an end*. Thus the *indication in trajectory data* would involve the detection of *inconsistent trajectory, loops, backtracking* etc. by the tools provided by the framework. This problem needs to be analysed based on context and typology.
- 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. 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 analysed layouts and *the actual occupant behaviour* is observed as *unintended usage.*
- Inflexibility: When space does not allow for customization for the occupant, it may lower spatial quality. Space should be designed adequately to suit changing design needs. Architectural design practice intuitively suggests that it is done to conform to minimum requirements of current needs of occupants. Flexibility as a feature of spatial quality is being explored in several domains. Open office is an outcome of the urge to find flexibility in office layouts. Organizational behaviour can be correlated with spatial quality in terms of flexibility (Varlander, 2012).
- Other Possible Influencing Fac-

Table 3. *Interpretation of Occupant Behaviour.*

	Behaviour Observation			**Behaviour Interpretation**	
				Possible Influencing Factors	
	Indication in Trajectory Data	***Observed Occupant Behaviour***		**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	*Repellents: 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(Context and typology based analysis is needed)	*Not Specified*
	Unexpected crowd in certain zones	*Unintended usage*	⟺	Unpredictable Usage	*No assigned space for certain functions/needs*

tors: *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 behaviour.

Among this extendable list of identified layout problems, the first seven problems were picked to limit the scope for the research. It should also be noted that occupant behaviour can be highly subjective and is closely related to the type and use of buildings. A problem in one context can be a desired feature in another. Future research on behaviour interpretation should take into account typology of buildings while using the framework for analysis.

4.4. Performance evaluation

Upon the interpretation of behaviour based on analysis of trajectory data, the final stage where evaluation and assessment of the layout follows. With the future development of quantitative evaluation criteria with measurement units and scales, an overall layout evaluation can be possible. Overall assessment can also take into consideration possible preferences and weights for criteria. A possible set of criteria is provided in [Table 4].

5. Proof-of-concept implementation

The occupant navigation is affected by elements of layouts classified into four layers [Figure 1]. The top occupant layer that this research focuses on, is where TDPF is designed to operate on. Occupants using a specific space are analysed.

An operational implementation of the Trajectory Data Processing Framework 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 [Figure 3]. It handles data related to spatial layouts. It is developed as a toolkit that includes input, processing and output tools for trajectory analysis. OLIA allows users to run operations on trajectories. It receives data from list sources such as Excel sheets. 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. Currently the OLIA toolkit requires users to be familiar with Visual Programming and Grasshopper.

5.1. OLIA tools and operations

Tools and operations in OLIA comprise a set of basic analytical operations that create, modify, edit and analyse trajectories. These tools and operations are explained individually below:

5.1.1. Create trajectory

With *Create Trajectory* [Figure 4a], the user can import point lists into this software environment. 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/sec.*

Table 4. *Layout Evaluation Table.*

	Behaviour Observation			Evaluation			
				Assessment			
	Indication in Trajectory Data	Possible Layout Problem		Criteria	Units	Constraints	Weight
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, Occurrences	Degree, times	>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

5.1.2. Number of trajectories

The operation Number of trajectories counts trajectories based on the order that they are created within OLIA environment. This tool comes with its own tagging function that enables the user with the ability to track trajectories according to their numbers.

5.1.3. 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 [Figure 4b] and list the points as coordinates in x, y, z format.

5.1.4. 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 4c]. It find the shortest distances between curves that are being analysed, at which points those curves come closest and sorts them.

5.1.5. Angle of deviation

Angle of deviation is a tool for analysing 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.

5.1.6. Intersecting trajectory lines

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 analyse [Figure 4d]. 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.

5.1.7. Average of trajectories

Computing the averages enables controlled simplification of trajectory data for layout evaluation framework. This operation computes midpoints of corresponding points on the trajectory curves that are being averaged [Figure 4e].

5.1.8. 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 [Figure 4f].

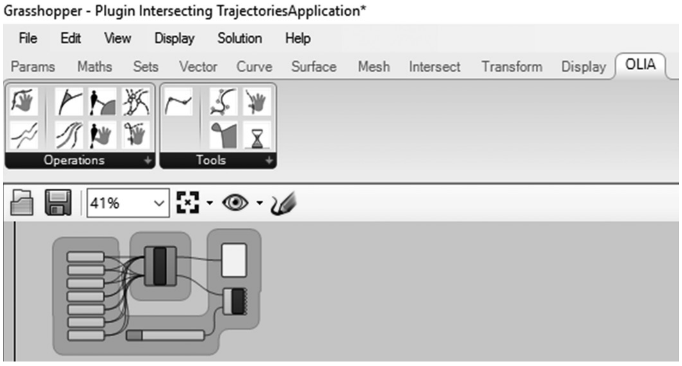


Figure 3. *OLIA plugin user interface on Rhino/Grasshopper.*

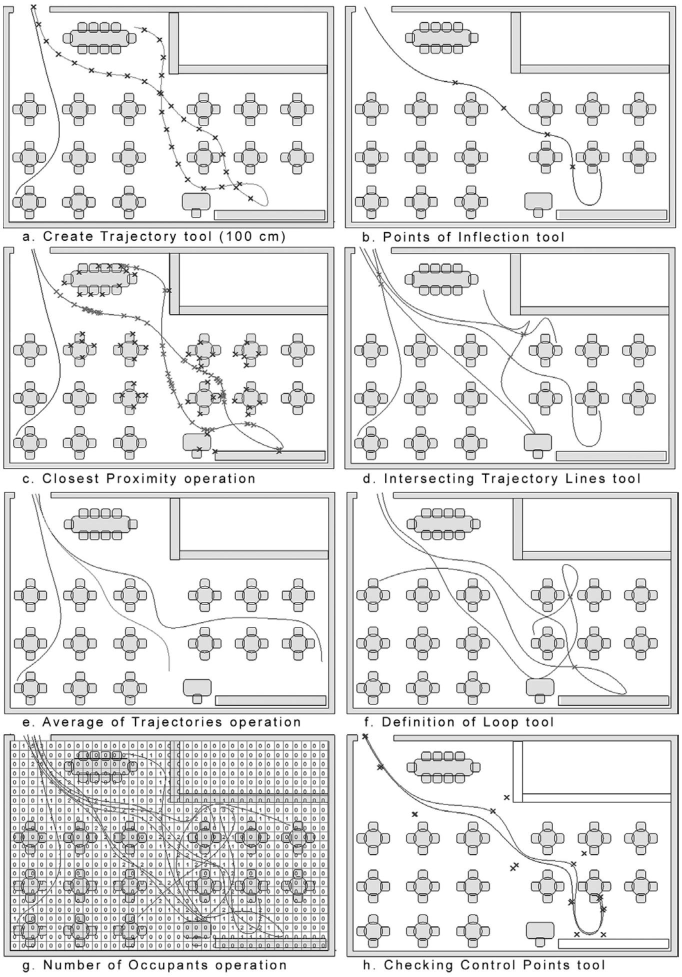


Figure 4. *OLIA tools and operations.*

5.1.9. Number of loops

This operation is for counting how many loops form on trajectories based on the definition of loop given by the user. *Number of Loops* yields lists of quantity values for loops forming on each trajectory separately. As stated earlier, the number of loops formed on trajectories showing occupant navigation behaviour indicates possibilities of difficulty in wayfinding.

5.1.10. Number of occupants

Based on trajectory data, it is possible to calculate how many occupants use each location in a specific space [Figure 4g].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.

5.1.11. Checking control points

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 4h].

5.1.12. Time data entry

While creating trajectories on layouts temporal data is entered. 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.

5.1.13. Speed

With OLIA it is possible to calculate speed based on the method that trajectories are created and analysed timewise. Once the timestamp and coordinate data has been captured, speed tool is operational.

6. An illustrative case for OLIA use

In order to demonstrate how objective metrics based on quantitative analysis can complement subjective evaluation data, a case study on the evaluation of a spatial layout has been conducted. The selected case is Faculty of Fine Arts (FFA) Café of Izmir University of Economics (IUE). It has a capacity of 60 seats and is among the busiest service spaces on campus. This space has been analysed with both manual tracking of occupants, an expert panel, and a questionnaire. Later, the subjective evaluations and objective data analysis results are compared. Here, the focus will be on this comparison. It should also be noted that during the course of this research the place has been reorganized with a new layout and this is utilized as an alternative layout in the analysis of the same space.

6.1. Subjective evaluations

Users of the FFA Café were surveyed for their experience of the space using a questionnaire. 13 questions were asked to 107 customers/occupants of the café who were students, faculty or staff and who regularly used the space. None had any disabilities. 5-point Likert scale (Krosnick & Presser, 2010) questions as well as short answer questions were used. Visual material depicting the spatial layout of the café with a grid of zones was integrated with the questionnaire to help respondents to mentally trace their experiences of the place.

One question asked respondents to identify layout problems that they observe in this space. They were allowed to check multiple items from a given list of possible problems. The answers to this question carried the problem of *over-crowding* to the top. 68 respondents observed over-crowding. Second came the problem of *unpredictable usage of space* (29 responses) and third came *wasted space* (21 responses). Following were the two problems that were *clutter*, *indirect access* and *bottlenecks*; each observed by 20 respondents. Least observed problems were *Insufficient Clearance* (18 responses) and *Inefficient Wayfinding* (12 responses). 6 respondents did not observe any problems and 7 respondents were undecided.

One question asked respondents to what degree they agree with the statement, "*I try to avoid certain areas in this place*", and mark those areas on the provided layout. 65 of 86 responses for the question specified the areas *avoid-*

ed. A total of 11 zones were identified. While one can expect that avoided areas are unused and over time perceived as wasted spaces, the results showed no such relationship between the results for avoided spaces and wasted spaces. However, there was a strong match between avoided zones and *over-crowded* zones when respondents were asked to identify them [Figure 5]. One can conclude that occupants avoid *over-crowded* spaces. Yet, when occupant movements are observed, the data provides a more complicated picture as discussed in the next section.

Responses of occupants depend mostly on their perception. They are subjective. Identifying patterns of behaviour through analysis of objective tracking data may lead to a more robust evaluation and understanding of occupant behaviour and performance of a spatial layout.

6.2. Objective data analysis

During *data acquisition* stage, movements of 120 occupants were tracked and recorded manually in FFA Cafe. Trajectory data was saved as Excel spreadsheets which were used as input for trajectory analysis in OLIA.

During the trajectory analysis stage, the *vector-based* trajectory data from Excel files were used to create the visual splines in OLIA environment. 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.

Figure 6a displays the resulting visual and numeric output in OLIA for counting occupants per zone at a resolution of 2.2 m. That is the same resolution set for the image used in the questionnaire. The *Number of Occupants* operation is displayed here with 60 of the trajectories recorded for visual readability. The numbers within each zone display how many times each zone has been visited. It can be seen from this analysis that although respondents of the questionnaire did not specify any over-crowding issues in the central zone of the plan, the real over-crowded zones are the four zones between the Entrance and the Payment point with 106, 62, 53, and 88 visits respectively. This contradicts the questionnaire results that suggest over-crowded zones are near the door to the Terrace. The same *Number of Occupants* operation can also be used to analyse the data in more detail, at a higher resolution of 0.5 m. The results are shown in figure 6b.

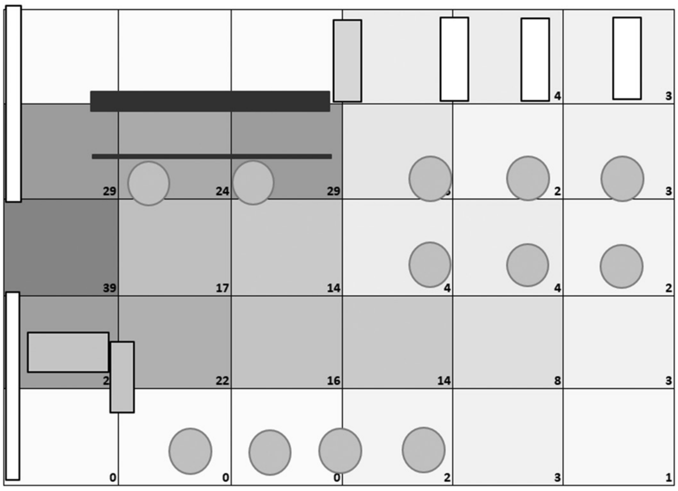
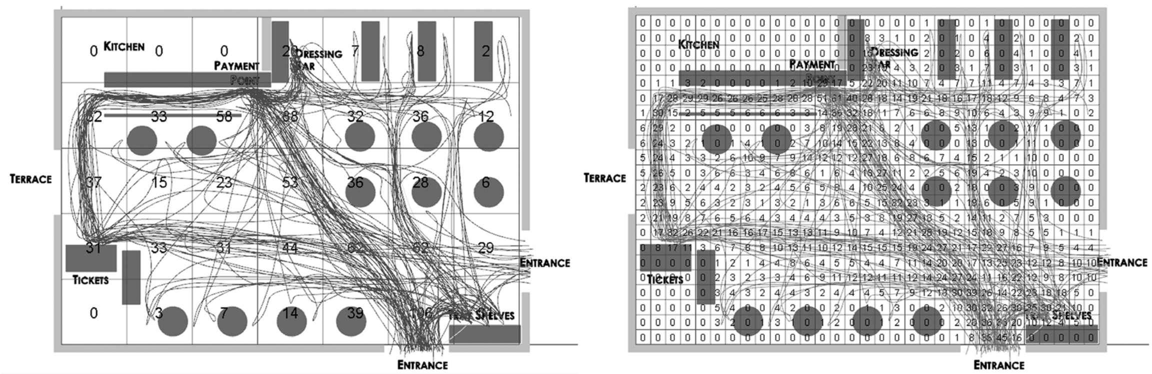


Figure 5. Total number of respondents that mark each zone as over-crowded.



a. grid resolution: 2.2m

b. grid resolution: 0.5m

***Figure 6.** Outputs of OLIA operation Number of Occupants.*

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. Such as the case of over-crowded areas in the evaluation of this café layout. 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. Therefore, the case is to illustrate that a methodology for quantitative evaluation of spatial layouts is operational although it needs further improvement. Accurate behaviour interpretation will require much more data than any one study can provide. As data expands, the research will include detailed definition and classification of occupants. Another concern about the questionnaire is that as the respondents displayed a very homogeneous crowd. The questionnaire will also be designed to collect more demonstrative data to represent all occupant types and their views on layout problems as a whole.

Research presented here, simply provides a platform for objective data analysis, hoping to enable more research on behaviour interpretation. Similarly, once a framework for robust behaviour interpretation is in place, overall performance metrics for spatial layouts can be proposed.

7. Discussion

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. The lack of a general framework for occupant movement analysis is the gap our research is trying to fulfil. Many researchers are interested in occupant movement tracking, but there is no general framework available, yet. Our work provides an infrastructure for other researchers, so they do not have to develop their own analysis tools. This is why the framework is the contribution and why it is intended to be general purpose.

This research first proposes an overall spatial layout evaluation methodology for quantitative analysis of occupant utilization of spaces. The four steps of the evaluation methodology are: *Data Acquisition, Trajectory Analysis, Behaviour Interpretation* and *Performance Evaluation.* Following this methodology, it will be possible to identify when and where problems emerge in spaces and even set standards, all based on *objective* data. Of course limitations exist. As mentioned earlier, occupant trajectory data acquisition is currently limited to displacement and movements of the body as a whole. Head and/or body rotation is currently not considered. Furthermore, mobile elements of layouts are considered as stationary and the change in their organization defines alternative layouts for which data needs to be collected separately. The extendable trajectory analysis framework developed here is designed to allow consolidating and making sense of the high volume of data automated occupant tracking systems will collect. It is expected that by using the framework, future work will focus on the third and fourth steps of the methodology, namely Behaviour Interpretation and Performance Evaluation. These steps require investigating how to identify patterns in trajectory data, match these patterns with actual human behaviour, identify layout problems, and finally define quantitative performance 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, though it can also be converted to other scripting languages on other software as well as other visual programming environments.

8. Future work

In its current state of development, OLIA allows occupant trajectories to be used in plan layout evaluation processes. However, the quest which TDPF is initiating, will not be complete without the development of overall performance evaluation metrics – maybe a *Layout Evaluation Score*. Reaching overall performance metrics requires developing evaluation criteria through studying causal relationships between spatial layout problems and occupant behaviour. TDPF is intended to be a research platform to enables 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.

Quantifying, that is translating experiential/tacit knowledge into datasets, relations, actions, operations, values, raises the scalability of systems. In the long term, quantitative evaluation of layout performance may contribute to automated spatial layout evaluation. Also, authors anticipate that it will be possible to assess larger and more complex buildings with several floors, linked by staircases, elevators or escalators at a later point.

TDPF and OLIA tools can also be improved with machine learning techniques and applications. Data acquisition method used in this study can be improved or replaced by data extraction methods using *Computer Vision* through which object detection and tracking may enable creation of rich datasets containing features of occupant behaviour and spatial layouts. Given that each occupant is producing huge amounts of data each moment, data will be abundant. However, the cleaning and sorting of data will still be a challenge where TDPF may provide an efficient template for spatial layout evaluation. 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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