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3D Physikalisierung von Migrationsbewegungen in Europa

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3D Physicalization of Migration Flows in Europe

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Erklärung zur Verfassung der Arbeit

Marian Bramberger

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Kurzfassung

Ursprung-Ziel Karten visualisieren die Ursprünge und Ziele verschiedener Bewegungen zwischen zwei Orten — den Ursprüngen und Zielen. Meist werden diese Bewegungen in Form von Pfeilen oder Pfaden zwischen Ländern oder Regionen dargestellt. Zwei zentrale Aspekte dieser Arbeit ist einerseits die Integration von der dritten Dimension, um damit den Faktor Zeit zu visualisieren und andererseits um eine Physikaliserung zu schaffen. Dabei soll diese Repräsentation eine neutral und leicht lesbare sein in Bezug auf Migrationsbewegungen im europäischen Raum. Dafür werden die Daten von Eurostat genommen. Um klare Ursprung-Ziel Karten generieren zu können, stützt sich diese Arbeit sowohl auf die Design-Richtlinien von Jenny et al. [JSM+18], als auch auf den Force-Directed Layout Algorithmus von Jenny et al. [JSM+17]. Diese Karten werden auf transparenten Folien gedruckt und in eine 3D-gedruckte Vorrichtung gegeben, um sie somit überlappend beobachten zu können. Dies resultiert in einem sogenannten physikaliserten Raum-Zeit Würfel, der es ermöglicht, Migrationsbewegungen über einen bestimmten Zeitraum zu beobachten.

Abstract

Origin-destination (OD) maps are geographical visual representations of movement between two locations — the origin and the destination. Typically, these movements are represented as paths or flows between two or more regions or countries. Two central aspects of this work are the integration of the third dimension to integrate the factor of time and bringing this visualization into the tangible space. The goal of this work is to create a new perspective to view migration flow patterns most neutrally and easily. That is why the data are taken from Eurostat, the European Statistical Office. To ensure that visualizations meet specific design guidelines, such as clarity, readability, etc., a force-directed layout algorithm was implemented based on prior work by Jenny et al. [JSM+17]. With these maps printed on overhead transparencies and in combination with a 3D-printed device, it is possible to stack the OD maps and compare them. The result is a physicalized space-time cube (STC), which offers a new way to look at origin-destination maps and enhance their interpretability.

Contents

CHAPTER 1

Introduction

Humanity employs many different ways to visualize data for different applications. The earliest roots of this concept are found in the creation of the first maps, which date back to the ancient Egypt surveyors, who used coordinates to lay out towns [Fri08]. Card et al. [CMS99] define visualization as "The use of computer-supported, interactive, visual representations of data to amplify cognition". Maps, charts, graphs, and dashboards are only a few possibilities to convey such information, while all of these representations aim to analyze and identify patterns as well as difficult concepts.

In particular, origin-destination maps (OD maps) are a special type of so-called flow maps indicating movement between places, whereas nodes represent origins and destinations. Typically, the movements are defined by paths, including encodings for information like movement value and direction [JSM+18]. OD maps ignore the actual trajectory route of the movement and focus only on the starting and ending points. However, OD maps pose challenges, like visualizing huge datasets and normalizing values to present accurately and truthfully. If not handled correctly, such challenges can decrease the readability, generate information loss, and mislead viewers [GZ14].

This thesis addresses these challenges on the topic of migration flow mapping in Europe. Since the intention is not to replicate previous OD maps, I will try to give a new way to look at such maps by introducing the factor of time. With that, a new challenge arises, hence, OD maps are usually built in a two-dimensional space. This means that they leave no other planar dimension available for representing the factor time.

To answer this, I introduce a third dimension in the form of a space-time cube to get the capability of handling another variable. These are often used for visualizations of spatiotemporal data, i.e., data that have both spatial and temporal values [GAA04]. Furthermore, STCs help to explore geospatial patterns, like understanding the movements of humans through space [Kra03]. However, space-time cubes bring their challenges in virtual 3D applications, as they could suffer from occlusion and distortion, which again can negatively impact the users' experience [BPF14].

By using data physicalization, I explore other aspects of the space-time cube metaphor. The OD maps are printed on overhead transparencies and combined with a 3D-printed fixture. Further giving viewers a new way to interact with OD maps and time. This tangible object allows users to interact intuitively with the physicalization, which, as research shows, can enhance the efficiency of information retrieval tasks [JDF13]. To sum up, the **research question** that this thesis aims to answer is "How can physicalization techniques and space-time cube operations enhance the interpretability of origin-destination maps for migration flows over time?"

This thesis' **contribution** is a new perspective on origin-destination maps, to not only show one specific point of time in one instance of an origin-destination map but to show a whole period by using a space-time cube. By using physicalization, I try to achieve a simpler approach for users to read and visualize the migration flows in Europe over time. Further making it more accessible for general users and not only analysts. At the end of the thesis, I am going to compare this approach to an augmented-reality model of the same problem and highlight the benefits of this physicalization.

Contribution Statement This project was partially done in collaboration with Gabriel Walchhofer. We worked on processing the dataset and the implementation of the layouting algorithm together. Subsequently, we developed a different virtual and physical embedding, respectively.

CHAPTER 2

Related Work

To further understand topics relating to this thesis, this chapter reviews the existing research behind the thesis and provides a general overview of approaches relevant to data physicalization and origin-destination mapping.

2.1 Data Physicalization

Data physicalization (or physicalization) refers to the act of creating a physical data representation to aid people in exploring and communicating complex data. Jansen et al. [JDI+15] describe the term physicalization as a "physical artifact whose geometry or material properties encode data". Nevertheless, not every object representing some kind of data is automatically a physicalization.

Figure 2.1: Physicalizaton of a 3D bar chart[JD13].

This approach is often categorized into two different classes: static and dynamic physicalizations. Static ones embed their data directly into their design and are not changeable. These are often haptic variables, for example, structure, shape, and texture, whereas active exploration is needed to comprehend their meaning [HHHvK23]. Dynamic ones can change their representation by user interaction [MVHB+21], as shown in Figure 2.1. An example would be the use of Lego bricks, as Ambrosini et al. [AM22] did. They created a new role play for a class of school children, where they needed to gather information and represent them with Lego bricks. Nevertheless, there are also approaches to dynamic physicalizations, which update themselves by adding virtual displays or other computer-driven control mechanisms [JDI+15, DJVM20].

Aside from haptic variables and interactions, physicalization offers other variables to encode information similar to visualization. For example, visual variables, including light, material patterns, or color, tend to be one of the most efficient options because the human brain can easily handle and interpret such visual information [HHHvK23]. For example, Rase [Ras12] created a physicalization on geospatial data, in which he visualized the distance to the next airport in minutes by encoding time in color and height. Furthermore, he concluded that estimating distances and heights is easier with a physical model than with 2D drawings. Additionally, Moorman et al. [MDES20] found that using geospatial physicalizations can support geographic learning.

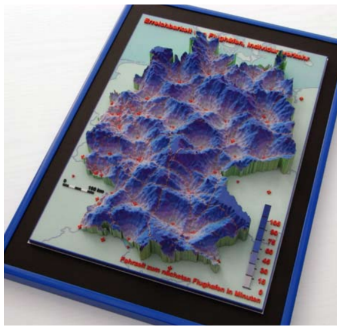


Figure 2.2: Physicalizaton of Rase [Ras12].

All of those aspects are brought together to form a space of opportunities for physicalization and show how one could use them to communicate data in a new form. Since humans developed a complex sensorimotor system, they have many options to gather information from the physical world [JDI+15]. Through our visual sense, we can easily inspect physical objects by turning them, moving them, or taking them apart. In contrast, visualizations strictly need active perceptional features implemented, which can still be powerful but also can create new challenges, like rediscovering and relearning. Furthermore, many non-visual senses can not be communicated via a computer but can still give additional information on objects, like stiffness, weight, or temperature. Additionally, those can be of great interest to visually impaired people. Lastly, Jansen et al. assume that physicalization could offer educational and cognitive benefits since their predecessors — physical representations and models - are already widely used in educational contexts, suggesting that similar advantages may extend to physicalizations [JDI+15].

2.2 Origin-Destination (OD) Maps

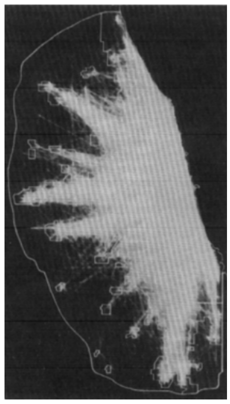
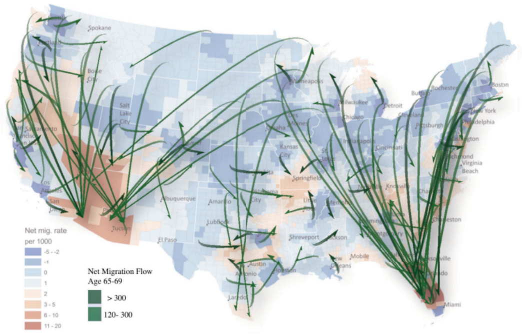
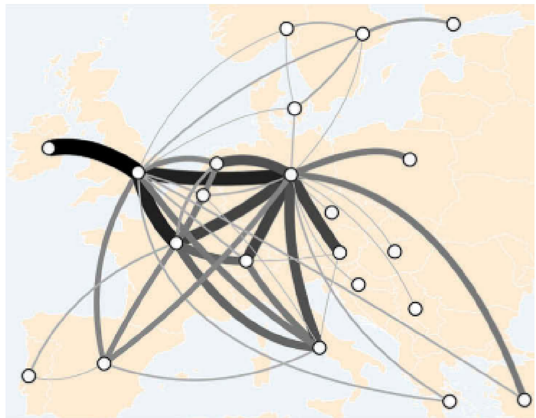


Figure 2.3: Representation of 9.931.000 desire line traces of trips in Chicago[Tob87].

Origin-destination maps are widely used to represent and analyze flows between regions or areas, generating insights into movement patterns, trade, or migration [Tob87, KTW23]. The first device to draw flow maps, the supercategory of OD maps, is called the “cartographaton” from 1959. The device was constructed as a ray tube system, already displaying several millions of lines, representing trips. These maps were used to improve the positioning of new expressways for Chicago [Tob87]. Figure 2.3 shows one of the earliest productions. While this OD map would classify as a static map, newer approaches also include interaction and dynamic approaches, for example, Stephen and Jenny developed a web-based application for county-to-county migration of the U.S. [SJ17].



(a) OD map from Guo and Zhu, showing migration flows between U.S. counties [GZ14].



(b) An example from Jenny et al. on how to encode movement values via color brightness [JSM+18].

Figure 2.4: Example Images between two designs of OD maps.

Also, Jenny et al. [JSM+18] identified guidelines for OD maps. This paper performed a quantitative content analysis of 97 flow maps and conducted a user study to gain insights into the effectiveness of the identified design principles, including the number of intersections, a representation of direction, and a representation of different quantity values. They concluded that the number of flow intersections should be minimized by curving longer flows more than shorter ones. Furthermore, that quantity is best shown as the width of the flow or otherwise via color brightness, and direction is best represented with arrowheads, accordingly scaled to the width of the flows [JSM+18].

While Jenny et al. concentrated more on the design of flow maps, Guo and Zhu [GZ14] focused more on generating flow maps with huge spatial mobility data. Furthermore, they presented a new approach to constructing and showing major flow patterns by combining a flow-based estimation method and a flow selection method for the normalization and smoothing of flows within a neighborhood. Lastly, Guo and Zhu propose that their visualization method can be further improved in terms of visual clarity, layout, and spatial modeling. Regarding 3D visualization, Yang et al. [YDJ+19] created another interesting approach for OD maps in combination with virtual- and augmented-reality (VR/AR) headsets. Furthermore, they explored the possibilities with an additional dimension and asked if the 2D OD map would still be the best representation or whether some other visualization, which uses the third dimension, could improve the visualization. The findings of their appended user study were that 2D OD maps are not the best representation technique for a 3D immersive environment. Furthermore, using 3D visualizations can help with challenges like overlapping flows since humans can easily rotate the model to resolve such problems [YDJ+19]. While the use of 3D visualization in combination with AR/VR techniques has been proposed to address spatial perception [Ras12], the application of data physicalization to OD maps is largely unexplored.

In summary, the main challenges of OD maps are handling big data tables [Tob87, GZ14] and consequently layout techniques [JSM+18]. The former problem needs to be handled according to the context of OD maps, one approach could be as Guo and Zhu [GZ14], to use strategies like clustering and sampling. Another approach, as Tobler [Tob87] suggested, is to just delete movement below a certain threshold, whereas the optimal deletion strategy would be to remove all values below the average table entry. Regarding layout techniques, Guo and Zhu addressed the problem by summarizing, generalizing, and normalizing flows and therefore preventing duplicate information and cluttering [GZ14]. On the other hand, Jenny et al. [JSM+17] provide a more accurate technique by introducing a force-directed layout approach on all the flows of the map. By calculating different forces on various points of the flows, they get pushed away from each other and avoid overlaps, improving the clarity of the OD map [JSM+17]. In this thesis, I will implement this algorithm and further make use of the design guidelines that Jenny et al. [JSM+18] provide. Furthermore, making it possible to create OD maps for specific countries of Europe, which represent the Immigration of such countries for individual years.

2.3 Space-Time Cube

The concept of a space-time cube originally appeared in 1970, when Hägerstraand [Häg70] introduced a new concept for space-time geography. His framework was built so that the geographical space collapsed on a two-dimensional space, and the third dimension (z-axis) represented the time, which increased with the height [HDAL99]. For him, the importance lies in understanding that locations should not only have geographical coordinates but also time coordinates. Furthermore, he proposes that the understanding of human behaviors requires the linking of where something happens and when it happens [Häg70].

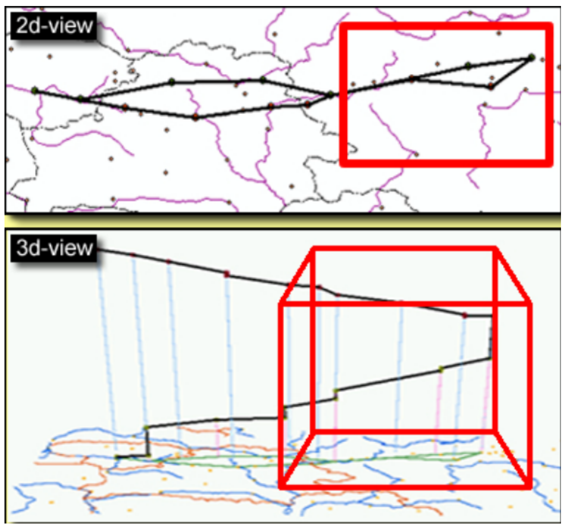
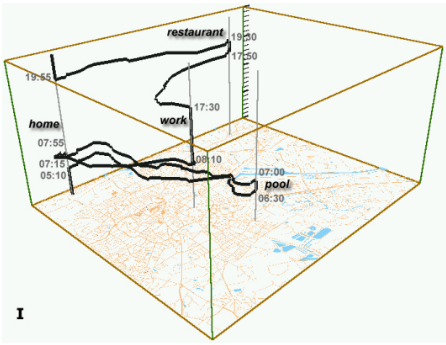
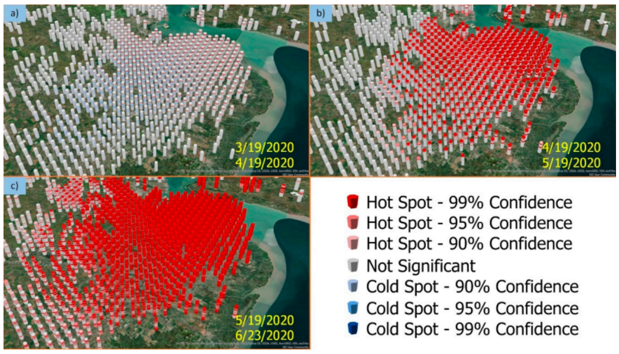


Figure 2.5: 2D and 3D view of Kraak's [Kra03] presented geovisualization application. The two red rectangles present the same STC from 2 different views.

Since then, many other researchers have readdressed his framework. Kraak [Kra03] presented a dynamic visualization environment with extended interactivity. An example shows how the new environment visualizes the march of Napoleon into Russia in 1812. Further into the paper, he claims that this scan can be used for real-time monitoring of running events, for example. At last, he concluded that the space-time cube representation is most suitable for displaying and analyzing paths of individuals, groups, or other objects moving through space.



(a) Space-time cube of Kraak, showing him taking a walk in the Netherlands [Kra03].



(b) Representation of COVID-19 hotspots in Surabaya Raya via a STC [PUH+21].

Figure 2.6: Example Images between different space-time cube visualizations.

In 2009, Kristensson et al. [KDA+09] claimed that there is still not enough empirical validation that space-time cubes are useful in conveying spatiotemporal patterns. They implemented a visualization for the movements of human walking traces on a university campus and conducted a questionnaire on 30 different people. This included questions about the time, the location, the number of persons at a specific time, and combinations of them. Lastly, they concluded that space-time cubes are not as efficient as two-dimensional representations in showing simple and direct queries, like finding a single event or comparison of two points in time. Nevertheless, they also showed that it is faster and more efficient in conveying complex spatiotemporal patterns. Within this thesis, the STC is used to create a representation of migration flows over time. Furthermore, I will make use of the different operations possible (juxtaposition, superimposition, etc.) within the STC metaphor.

However, space-time cubes do not necessarily have to show values of movement of objects. During the height of the COVID-19 pandemic, Mo et al. [MTM+20] and Purwanto et al. [PUH+21] presented visualizations showing the spreading of the disease over time. Both had a very similar approach, using pillars indicating the progression of time and different colors, representing the number of positive coronavirus cases. Purwanto et al. [PUH+21] concluded that combining an STC with a hotspot analysis can provide detailed insights into disease behavior. On the other hand, Mo et al. [MTM+20] found that using an STC for displaying spatial-temporal information can positively affect the analysis of an epidemic. Further enhancing the possibility of observing patterns and reacting to the outbreak more intuitively.

On the other hand, Bach et al. [BDA+14] proposed many different ideas on STCs, like not explicitly showing them in the final visualization or considering them as conceptual representations for visualization techniques and not only for 3D visualizations. Furthermore, they introduced operations like time cutting and time juxtaposing. The former is for extracting a single plane from the time dimension, and the latter is for extracting multiple planes and reordering them side-by-side. Furthermore, Bach et al. [BDA+17] conclude that STCs can be used for many other application domains, like dynamic network analysis, video analytics, or cartography.

2.4 Research Gap

Since the migration flow representations over time are little explored, I want to use the metaphor of the space-time cube in combination with origin-destination maps to create a new perspective on OD maps with periods. By further incorporating physicalization in this approach, I will utilize the benefits to improve the recognition of patterns and trends while enhancing the experience through a tangible and interactive representation.

By separating the OD maps from the physical map, I aim to create a dynamic side-by-side view of migration patterns over a map of Europe. Additionally, by using overhead transparencies, the goal is to create an interactive and engaging timeline view, allowing users to visualize changes in the flows over time, unlike traditional static visualizations. At the same time, this design still allows one to examine individual years, ensuring that users can still focus on specific periods.

CHAPTER 3

Method

In this chapter, I will give an overview of how I approach the generation of physicalized 3D OD maps. It covers a description of the underlying dataset, where it is retrieved, what information will be used thereof, and how it is manipulated and edited. Furthermore, I explain the design choices and layout of the OD maps for using them in the physicalized model. Lastly, I will briefly explain which technologies I use for the implementation.

3.1 Dataset

Since the goal is to represent migration flows in Europe in a very neutral way, I retrieve the dataset from Eurostat, the European Statistical Office. This department collects data from national statistical institutes for potential candidates for EU membership. Since they provide many different sets of multidimensional data, I identify the variables necessary to visualize migration flows. Since I visualize OD maps in the context of migration and based on Jenny et al. [JSM+18], at least the following four are needed:

- **Year**: Which year is currently in the scope of the analysis?
- **Origin**: Where are humans coming from?
- **Destination**: Where are humans going to?
- **Movement Value**: How many humans are migrating within the given year?

Nevertheless, Eurostat offers much more information on migration flow values than those four, including age groups, sex, and country of citizenship.

The dataset I used for this work originally had twelve columns and is effectively stripped down to the previously named four variables. Variables like "age group" and "sex" are not considered within this thesis since it should cover the migration in total. The migration flow numbers are based on the number of humans emigrating from their country of birth. Since I visualize the migration within Europe, the following country regions are included: Europe, the Near East, and North Africa. All others are excluded in the process of filtering the dataset. Furthermore, by deleting every row entry whose movement value is under 90% the mean value of the year, similar to Tobler [Tob87] suggested, I can reduce the size of the dataset drastically.

Lastly, my approach accepts different inputs that allow the dataset to be generated for specified countries, i.e., countries in which Eurostat has the immigration information. Furthermore, it is possible to generate OD maps for different European countries. In Figure 3.1, I show which countries act as destination countries, i.e., can be generated maps from, and which only act as origin countries. The orange-colored countries are destinations, but they are also possible origin countries. On the other hand, the blue-colored countries only represent origins. These are included in the final modified dataset.

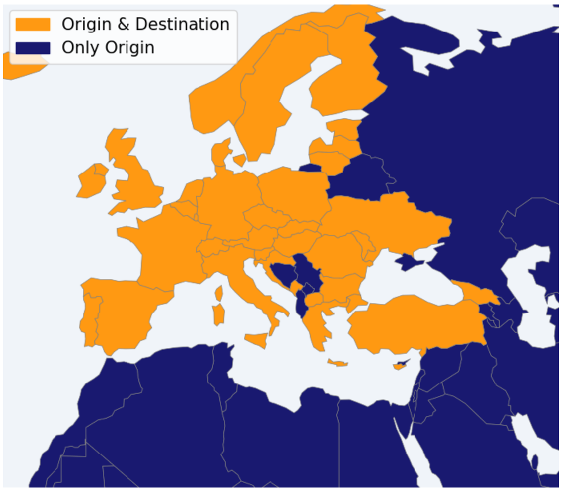


Figure 3.1: Orange countries are destination and origin countries, blue colored countries are only origins.

3.2 Design Goals

Before explaining the individual methods used in detail, I define a set of design goals based on related work guiding this work. These principles define the scope of the project and highlight the key considerations for creating OD map physicalizations:

- **Comparability**: Conceptually, OD maps need to be easily readable and clear to decrease the error rate on information retrieval tasks, as shown by Jenny et al. [JSM+18]. This can be achieved by finding a layout for all flows following proven design guidelines. Therefore, it is necessary to use an arrangement algorithm, which automatically finds a solution for a given OD map. I use the algorithm offered by Jenny et al. [JSM+17], which provides a way to arrange flows based on forces. Since it does not take any trajectory of the flows into account, resulting in freely moving flows, it is well suited for this application. Furthermore, I want to compare those single OD maps when superimposed over a period, these consequently need to be laid out the same way over all years. Additionally, encodings of flow characteristics give further insights into the change of values over time. Jenny et al. [JSM+18] offered an approach to design guidelines, which this project is heavily based on. Their guidelines were proven to increase readability according to the use case. For example, these included having a minimal amount of overlapping flows or that sharp bends are avoided as much as possible and symmetrically curved flows are preferred. Additional findings are shown in Figure 3.2.

- **Interactivity**: Physicalizing OD maps are expected to allow for an intuitive exploration of migration flows by creating tangible interaction. A key challenge is to ensure that multiple OD maps can be effectively compared across different years. Users can view multiple OD maps at once, simply change the arrangement, or look at a single OD map at a time. Furthermore, the physicalization of the STC allows such operations and could offer further educational and cognitive benefits, as assumed by Jansen et al. [JDI+15]. As proposed by Bach et al. [BDA+14], time cutting allows one to look at a specific point in time represented as time slices. These slices offer further possibilities to be interacted with, for example, either by juxtaposing them, meaning arranging them side-by-side or superimposing them to gain further insights into patterns.

- **Versatility**: Furthermore, this approach must be adaptable to different analytical needs, creating possibilities to explore various patterns and insights. This includes flexibility in comparing different periods or focusing on specific countries. Since these representations rely on datasets, it is crucial to preprocess the data according to the task and identify key variables needed for visualization. For OD maps, this includes the movement value, the time frame, the origins, and the destinations. This already reduces the dataset size, and I can refine the size further with an approach offered by Tobler et al. [Tob87]. If these variables are not chosen and reduced correctly, the resulting origin-destination map can become misleading, cluttered, or difficult to interpret.

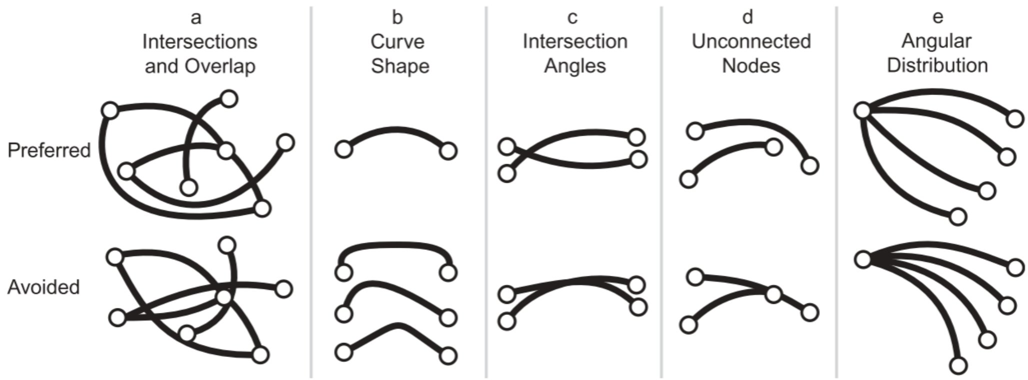


Figure 3.2: Design guidelines by Jenny et al. [JSM+18]. (a) minimal number of overlaps, (b) symmetrically curved flows are preferred, (c) avoid acute-angle crossings, (d) nodes should not be overlapped, (e) flows need to be distributed in a radially way around nodes

Establishing these design principles set the foundation for a clear and comparable representation of physicalized OD maps. The following sections will give a more detailed explanation of how specific methods are used to achieve those principles.

3.3 Design of the OD Maps

With a suitably processed dataset in hand, I propose a method to create proper OD maps. The main goal was to implement a design that ensures comparability, clarity, and effective representation of migration flows. To achieve this, a structured approach was taken to position flows to minimize overlaps and create a balanced visualization. The following sections describe the methods used.

3.3.1 Force-Directed Layout Algorithm

Conceptually, the algorithm offered by Jenny et al. [JSM+17]treats flows as quadratic Bézier curves and adjusts the positions according to surrounding flows and nodes. Those consist of three different points; one acts as a control point and shapes the curvature. The other two points represent the start and the end of the curve, whereas this is interpreted as the origins and destinations. For one OD map, all of the flows share the same destination since I construct the migration flow map for one single country, as shown in Figure 3.3. The quadratic Bézier curve in between those two points, further influenced by the control point, represents the movement value from the origin to the destination. According to design goal **comparability**, the trajectory of the flow does not have any further meaning. Additionally, quadratic Bézier curves are a suitable option for OD maps since they never contain loops, are not S-shaped, and are part of standard graphics libraries.

Figure 3.3: Italy is the current destination of the map. France and Germany are current origins. The names of the countries are not included in the final OD map.

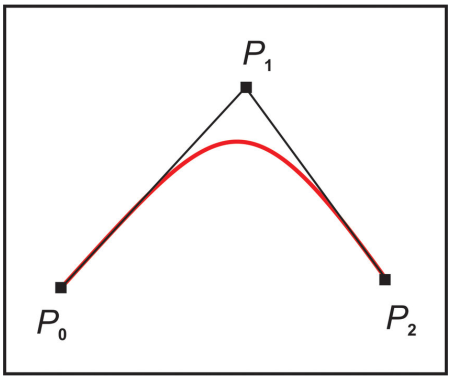


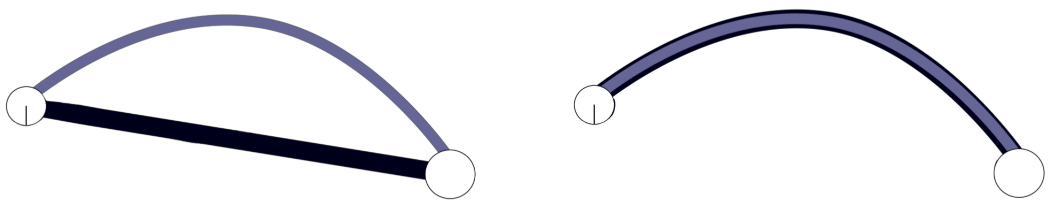
Figure 3.4: A basic quadratic Bézier curve. In my case, P0 could either be an origin or a destination, whereas P2 must then be the opposite. On the other hand, P1 is always the control point [SM22].

The control point of each flow is moved with various forces and controls itself with an attached spring to the midpoint. The midpoint is the half point of the line between the start and endpoint of the Bézier curve, shown as P1 in Figure 3.4. The repulsing forces, exerted on the control point, stem from other flows and nodes. Their magnitude of force is calculated based on various distances between their flow or nodes and other ones. Through an iterative process, these are recalculated and applied in every step. Nevertheless, the more iterations the algorithm goes through, the less weight the forces gain, achieving an equilibrium state, which cannot be changed easily in the later stage. In the last step of each iteration, Jenny et al. [JSM+17] move flows of overlapping nodes and arrowheads. However, this application does not include arrowheads because, on some occasions, many of them overlapped on the endpoint (interpreted as the destination country of migration flows). These overlaps should be avoided to increase readability, as Jenny et al. [JSM+17, JSM+18] suggested.

By using a different number of iterations and varying other weighting options for the forces, I can control the shape of the output curves. Keeping this constant between years preserves **comparability** as required by the design goals and based on the guidelines offered by Jenny et al. [JSM+18]. Therefore, I use a well-laid-out arrangement of the OD maps to represent the STC.

3.3.2 Design Choices for Superimposing

Since the final physicalization presents the flows over the years equally, as described in design goal **comparability**, the layout of the flows needs to be the same over the years. This enables the user to see visual changes over time by changing encodings over time. For example, if the flow from Germany to Austria has a different curvature in 2012 than in 2013, one could not see the change as easily, as shown in Figure 3.5. Therefore, the layout needs to be consistent between years, in particular when superimposed, as described in design goal **comparability**. Nevertheless, this design should also provide the viewer with a clear visualization, which can become difficult with an increasing number of input data [Tob87, YDJ+19].



(a) Two different flows between the same countries over different years and not aligned equally. (b) The same two flows overlapped according to the same base map.

Figure 3.5: Difference between overlapping of two flows and difference in visualizing changes. The left point is the endpoint/destination, including a marker, and the right one is the origin.

To make the OD maps comparable over all the years, it is necessary to know which countries are included in the dataset over the period and correctly lay out all of them simultaneously. To create a set of flow maps, I consider all possible origins and destinations for a range of years. Then, I calculate one flow map, including all of those points, and treat this as my base map. Furthermore, for individual years, I can automatically switch flows off, which will not be visible for that year. Using the same layout between the years makes it possible to superimpose those OD maps and further compare them over time, as required by the first design goal. Furthermore, I base my implementation on the layout algorithm proposed by Jenny et al.[JSM+17].

3.3.3 Encodings for Movement

I now propose to use visual encodings for three different aspects of migration flows: multiple origins, one destination, and movement values. The first two are represented by different nodes in the same color over the corresponding country. Whereas the node of the destination country includes a marker, as shown in Figure 3.5. It consists of a line from the center to the outline of the node and determines the orientation of the transparent OD map. This is necessary if there are scale differences between the physical map of Europe and the OD maps, for example, if the map of Europe is of the format DIN A3 and the OD maps are of DIN A4. Further, ensures the correct rotation of the overhead transparencies. I propose to calculate the size of the circles at the origin of the flow proportional to the corresponding flow size. The radius should always be bigger than the flow width.

Furthermore, the movement values of each migration are encoded in two ways simultaneously: the flow width and color. Firstly, the width is normalized over the averaged movement value of the period. Further limiting the lower and upper bounds of the width ensures that the size is kept appropriate for the size of the representation. The size of the nodes depends on the width of the flow and always has a slightly bigger radius than the width, achieving a clear connection between the flow and the node. The incorporated color further helps to identify changes in quantity [JSM+18]. Furthermore, it is closely coupled with the width of the flow and corrected with a sigmoid function to get better distinctions between values around the average flow width. It varies in saturation, meaning that the bigger the movement value is in comparison to the average yearly value, the bigger the saturation. Additionally, all the flows are colored in blue since blue is perceived as neutral and trustworthy, further improving the neutrality of this physicalization [EM14]. In combination with a saturation gradient, it can increase the effectiveness in the completion of tasks, according to a user study by Karim et al. [KKPL19].

3.4 Physical Model

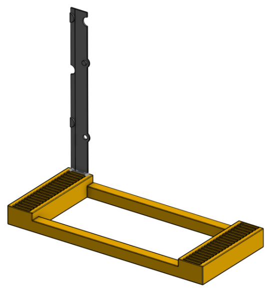


Figure 3.6: in yellow is the base plate, same as the top plate, and the one grey clamp is visible, based on Pahr et al. [PEF25].

I propose to use a physical model consisting of two parts: A map of Europe printed on a sheet of paper and the space-time cube physicalization, including the OD maps. These maps are printed on overhead transparencies. Since the concept is built around a space-time cube, the design of the physicalization is a cube-like device. I use the approach proposed by Pahr et al. [PEF25] introduced in their work. The 3D-printed model consists of a base plate, a plate on top, and two clamps for each side of the OD map, as partly shown in Figure 3.6. These clamps are used to stiffen the OD maps and put them into the base and top plate. This ensures a stable physicalization. Those maps can be freely adjusted and switched so that users can modify the STC as they like. Furthermore, the users can use single OD maps on their own and lay them on top of the map of Europe or juxtapose them, as Bach et al. [BDA+14] suggested.

To counteract the opacity introduced by subsequent slides, I printed an additional map of Europe. This can be used to freely put between two different OD maps to ensure clarity further. Furthermore, this also acts as a legend, showing the abbreviations of the countries in their nodes and their full names on the side of the overhead transparency.

Figure 3.7: A prototype of the final physicalization. One black base and one for the top whereas the latter will be added. The OD map is between the violet clips.

Figure 3.7 shows how the final physicalization should look like. The black part on the bottom is the base to put in the violet clips. Furthermore, another black part will be for the top of the clips so that the slides are stiffer. In between those two violet clips are the OD maps whereas those can be put one after the other, making it possible to superimpose those maps.

3.5 Implementation

This project was done entirely in Python in combination with a few frameworks. I used **Pandas** to process the underlying dataset accordingly. For the generation of the map of Europe and other geographical information, I utilized **GeoPandas**, whereas for mathematical calculations, **NumPy** was essential. When all of those calculations were done, **Matplotlib** was used for various plots of the OD maps and the map of Europe.

CHAPTER 4

Result

To showcase the result of my work, I chose the country of Austria to present the physicalization. For this example case, I am going to start by showing the OD maps combined with the map of Europe. Later, those are going to be shown on printed overhead transparencies and presented as physicalized objects, whereas the last part will introduce the physicalization of the STC. Afterward, I am going to briefly introduce two OD maps of the Netherlands to show the migration over the period for another country. In the second part of this chapter, I will break down how the earlier defined design goals were fulfilled.

4.1 Example Case: Austria

The dataset provided by Eurostat contains data from 2008 to 2022 for migration into Austria from 20 countries. Nevertheless, 2009, 2010, and 2013 are missing or lack detailed information on the disaggregated countries. For 2013, no separate breakdown of migration numbers for separate countries exists, and only a total amount is given. Therefore, I omitted data from this time for my case study. For better explanations, I introduced markers in the form of numbers to better guide the reader to the countries I will speak about. Those are not included in the resulting maps of this project.

4.1.1 Digital OD Maps

In Figure 4.1 and 4.2, I show the individual OD maps from the years 2019 and 2022. First, one of the main differences visible is the movement from Ukraine to Austria (indicated with 1). In 2022, it drastically increased from 1437 to 60787 people, which is shown by the flow width and the color. In 2019, it is relatively slim and less saturated, whereas in the second picture, the flow is the biggest of the OD map with a more saturated blue. Furthermore, big differences can be seen between the movements from Great Britain (indicated with 2) and Syria (indicated with 3), whereas Great Britain is not visible anymore in 2022. This means that for the year, the migration value of England must be below the mean of the migration over the period. For Syria, the migration values increased from 1426 in 2019 to 11142 in 2022. Subtle changes can be seen in Germany (indicated by 4) and Romania (indicated by 5). Both movements increased, but only slightly.

If looking closely, the amount of people coming in from Germany increases as shown by the area of the circle increasing, whereas, in Romania, the difference is too small to gather a change. These are only two OD maps of 12 in total. Furthermore, those were generated with 25 iterations, whereas I used other weightings of the forces that Jenny et al. [JSM+17] provide to increase the fitting for the layout.

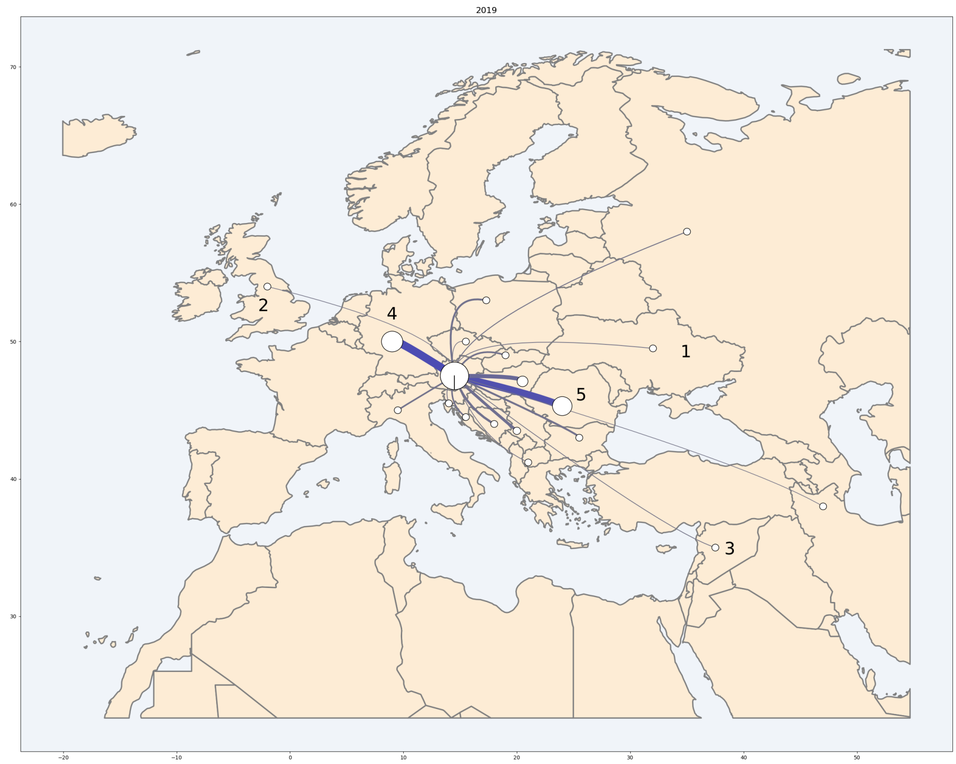


Figure 4.1: Digital OD map from Austria showing the migration of the year 2019. The migration from Ukraine (indicated with 1) is rather small and the flow from the United Kingdom (indicated with 2) is present.

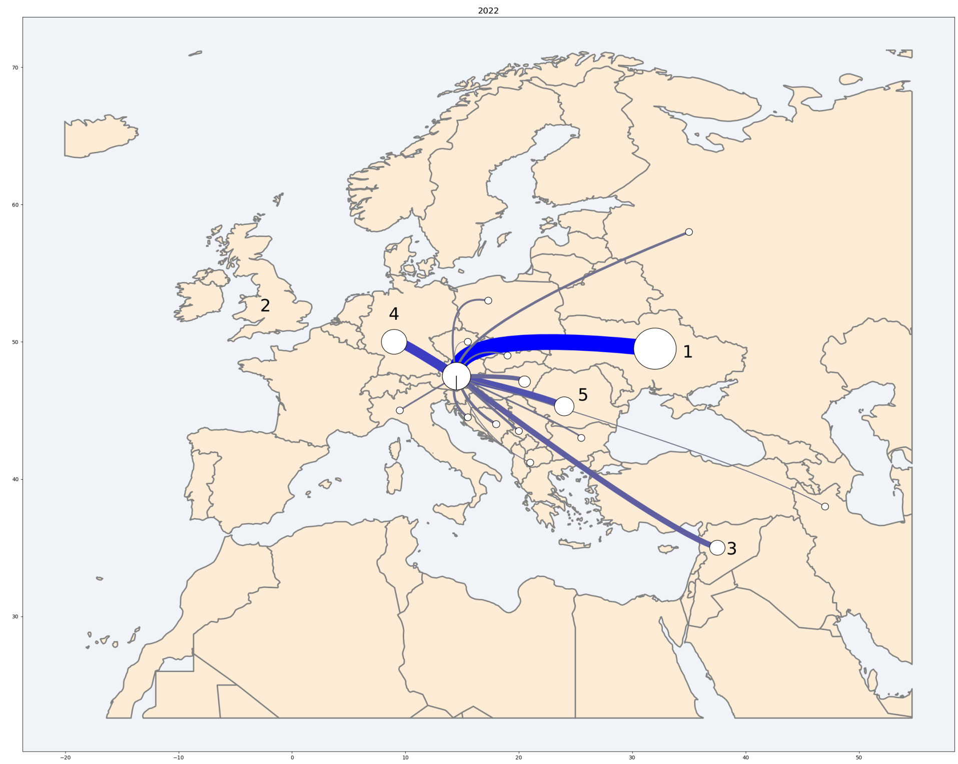
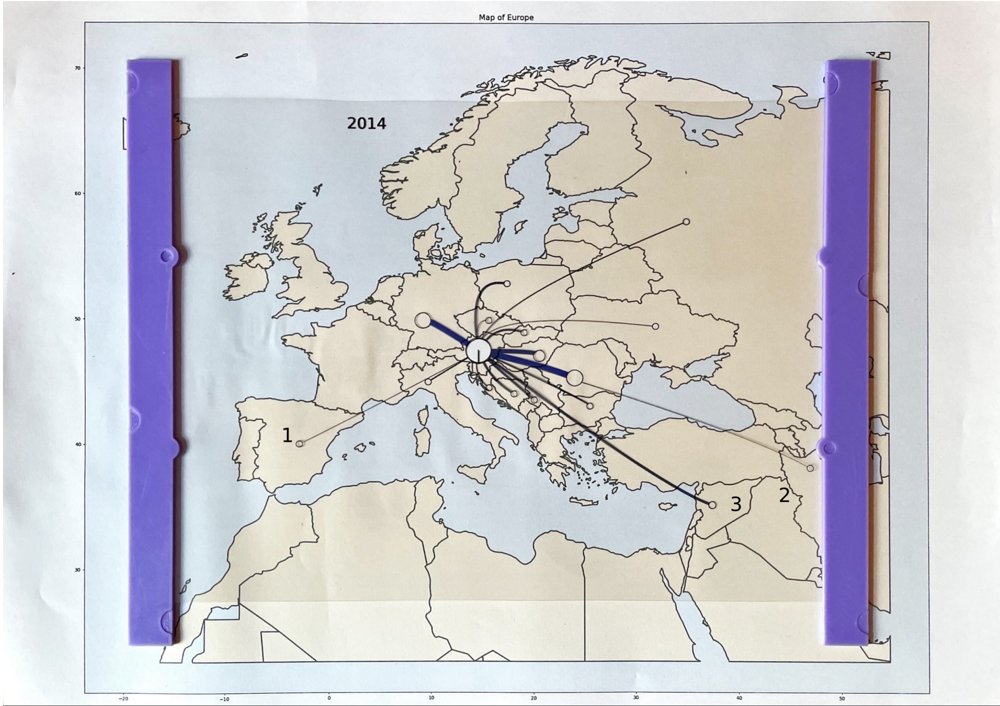


Figure 4.2: Digital OD maps from Austria showing the migration of the year 2022. The migration from Ukraine (indicated with 1) increased drastically and the flow from the United Kingdom (indicated with 2) vanished.

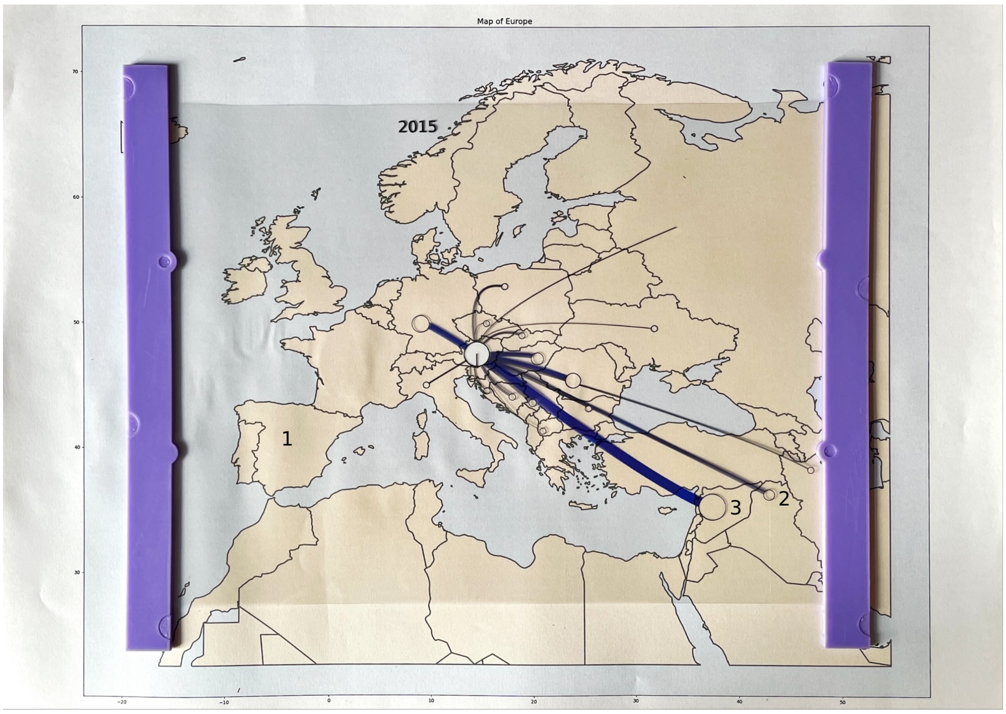
4.1.2 Printed OD Maps

Side-By-Side View In Figure 4.3, I show the different OD maps printed on overhead transparencies. Those are from 2014 (Figure 4.3(a)) and 2015 (Figure 4.3(b)), further presenting the migration to Austria. These two different years were juxtaposed for this representation, showing both maps side-by-side. The main differences visible are the vanishing of the flow from Spain to Austria (indicated with 1), the occurrence of the flow from Iraq (indicated with 2), and the drastic increase in flow width from Syria (indicated by 3). The occurrence of the latter movement can be due to the outbreak of the civil war in Syria in 2015. The migration of countries on the northern side of Austria stayed relatively the same over this time, based on the flow widths and node sizes.

The OD maps were separated from the Europe Map, ensuring interactivity and changeability as shown in previous examples. The Europe map is seen in previous Figures like Figure 4.3, whereas it always includes the destination node. This node, in this case, Austria, was generated as an aid for positioning and orienting the OD maps accordingly. The same node was also included in each OD map, whereas the line in the circle indicates the right rotation. Furthermore, the map was printed on DIN A3 paper, ensuring a big



(a) 2014



(b) 2015

Figure 4.3: Juxtaposed and printed OD maps on overhead transparencies showing the migration of 2014 and 2015. Changes in migration can be seen in Spain (indicated with 1), whereas it was still visible in 2014 but not anymore in 2015. On the other hand, migration from Syria (indicated with 2) and Iraq (indicated with 3) increased in t 2015.

enough size to gather information. The OD maps were scaled in a way so that they were able to be printed on A4 Paper but still match the dimensions of Europe. This choice was made to keep the costs of printing on overhead transparencies as low as possible since those can be more expensive the bigger they are.

Superimposed View Figure 4.4 shows the superimposition of OD maps from 2020 to 2022 in Europe. The latest year is at the top of the arrangement. The main differences visible are the growth of migration movement from Ukraine (indicated with 1) over the period and the vanishing of the flow from the United Kingdom (indicated by 2) to Austria. One can see the latter difference since there is only one node and a thin flow between the United Kingdom and Austria. At the flows of Ukraine, it is interesting to see how the opacity of the color behaves in contrast to others like Germany. For Ukraine, the flow of 2022 is the biggest, but this size appears only once, resulting in a less saturated blue. The flows of Germany have a more saturated blue, indicating constant movement. Furthermore, the flow width and node size of Germany (indicated with 3) stay relatively the same, which can be interpreted as not a big change in migration movement. This is similar to other countries like Italy, Croatia (indicated by 4), and Poland (indicated with 5). Nevertheless, in those countries, significantly fewer people migrated to Austria in relation to Germany. This behavior can be seen when comparing the flow width of the mentioned countries.

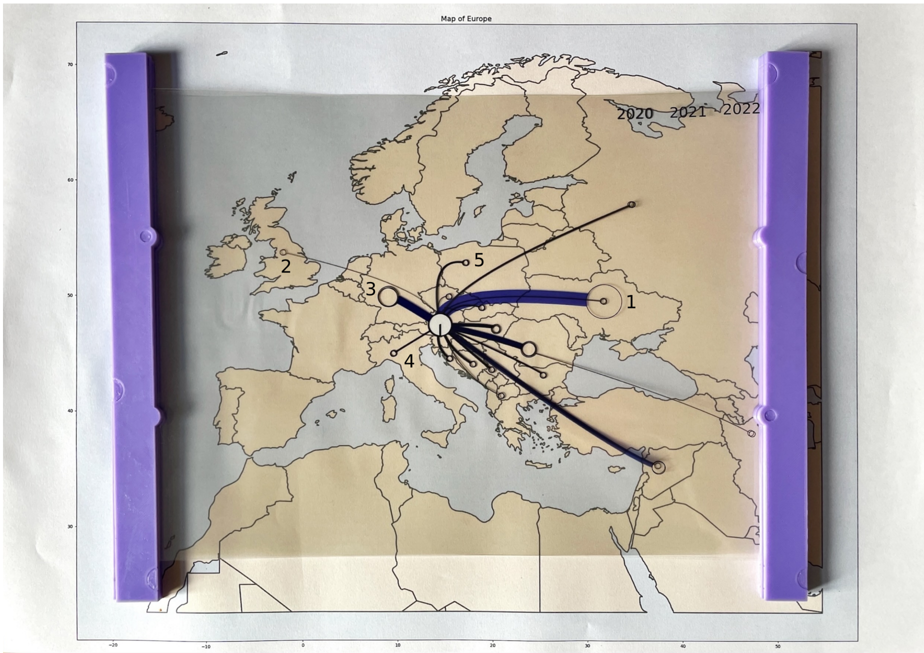
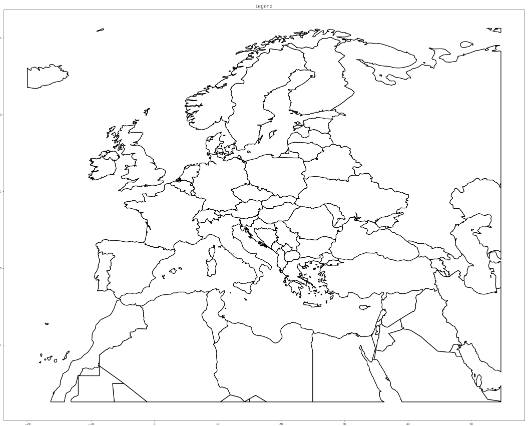


Figure 4.4: Superimposed view of migration to Austria with 3 OD maps from 2020 to 2022. Constant migration happened from countries like Italy, Croatia (indicated with 4), and Poland (indicated with 5), as well as the previously mentioned events of Ukraine (indicated with 1) and the United Kingdom (indicated with 2).

The two legends, seen in Figure 4.5, were created to further help the viewer identify the borders of the countries and country names. These can counteract the opacity introduced when many OD maps are superimposed, as shown in Figure 4.6. Figure 4.5(a) presents all the borders of Europe solely, whereas the legend in Figure 4.5(b) further introduces the country abbreviations inside the nodes and an explanation of those on the left.



(a) Legend with borders only.

(b) Legend with abbreviations and explanations (zoomed in).

Figure 4.5: Two different legends to counteract opacity.

4.1.3 Physicalization of the STC

The physicalized STC was the final result for this thesis and is shown in Figure 4.6. It shows the OD maps within the given period, from 2012 to 2022, with missing years (2008, 2009, 2010, 2011, 2013) and including the legends. I used the method proposed by Pahr et al. [PEF25] to arrange the individual maps and visualize a time progressing along the z-axis. The violet parts are clips, which are needed to stick the individual maps into the base (the black part). In this version of the physicalization, I also introduced a top part to further stiffen the maps and create a better superimposition.

In Figure 4.6, the mentioned events in this period are visible. For example, the sudden increase of Syria (indicated with 1) in 2015 is still visible and further occurred in a smaller amount in 2021 and 2022. This is better visible from an angled view, like in Figure 4.7(1). On the other hand, the migration from Germany (indicated by 2) to Austria stayed overall consistent over the period, indicated by the consistent flow width and size of nodes. The most present is the drastic increase of the flow from Ukraine (indicated with 3) in 2022, also because it was one of the most recent events. Furthermore, the occurrence and vanishing of the flow from the United Kingdom (indicated with 4) to Austria is still visible, even though the opacity makes it more difficult to see. In general, migration, which consistently happens from countries to Austria, appears darker than others. This effect occurs because of stacking multiple flows on top of each other. Additionally, indicating migration movement patterns over time.

Figure 4.6: The physicalization of the space-time cube including both legends. The first is positioned roughly in the middle of the slides, and the second one, without explanations, is in the back.

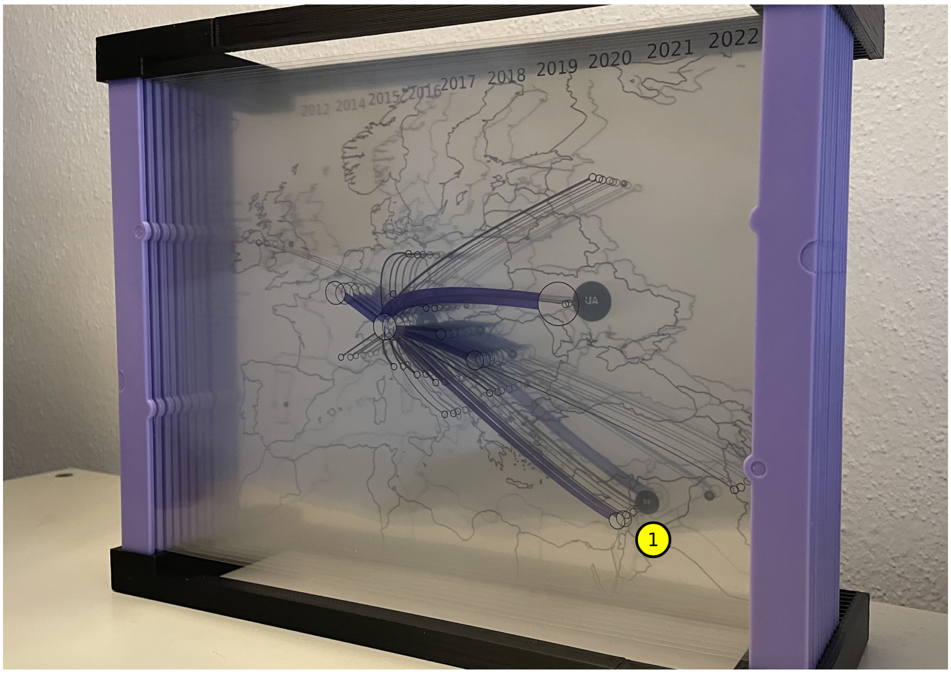
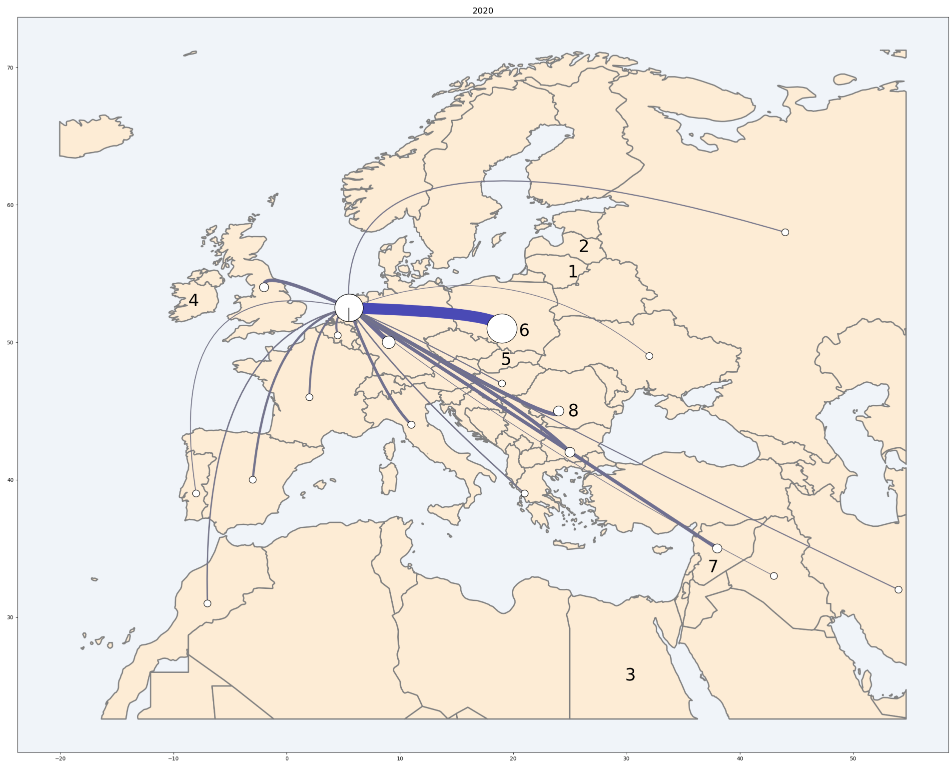


Figure 4.7: Space-time cube viewed from an angle to better identify the migration flow from Syria (indicated with 1) in 2015.

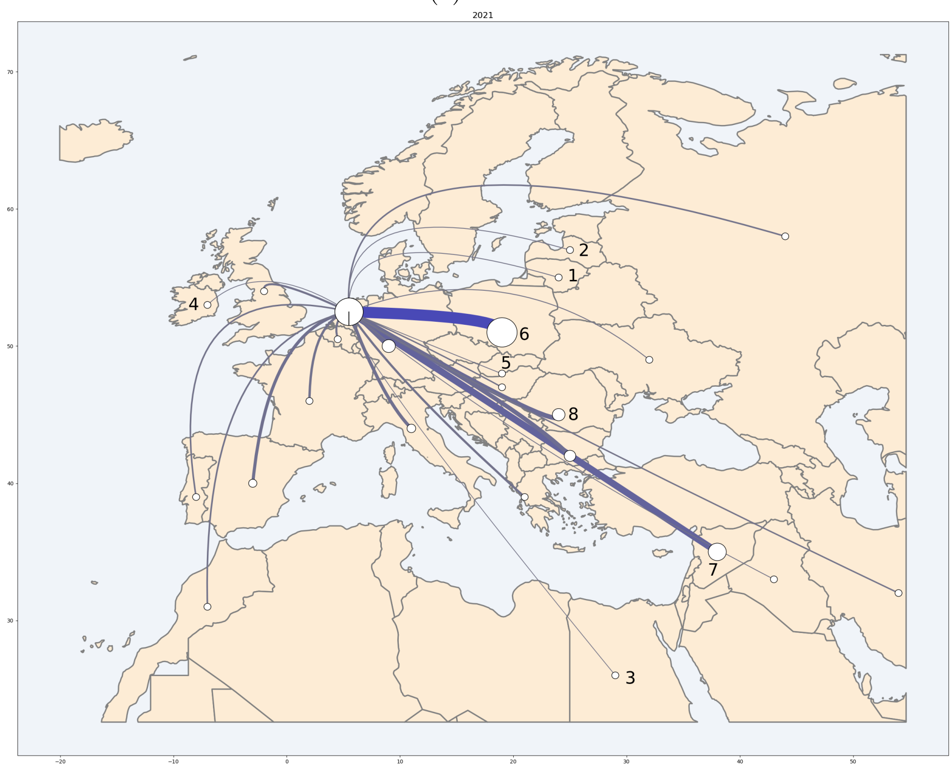
Figure 4.8: Showing the space-time cube without any legends and borders of Europe. A more abstract visualization of migration flows, without a map of Europe superimposition.

4.2 Example Case: the Netherlands

For the Netherlands, it was possible to generate all of the years from 2008 to 2022 since the data were available and were broken down into countries for those years. These OD maps were generated with 30 weighted iterations. The year 2020 is shown in Figure 4.9 and 2021 in Figure 4.9. In those two years, the main differences visible are the occurrence of the flows of Lithuania (indicated with 1), Latvia (indicated by 2), Egypt (indicated by 3), Ireland (indicated with 4), and Slovakia (indicated by 5) in 2021. For both years, Poland (indicated with 6) had the biggest migration movement value, but it stayed relatively the same as many other countries. However, migration from Syria (indicated with 7) increased in 2021, as migrated from Romania. These changes can be seen in the width and the color of the corresponding flows, whereas the increase in Romania (indicated by 8) is rather difficult to see since it was not a huge increase.



(a) 2020



(b) 2021

Figure 4.9: Migration movement of the Netherlands from 2020 and 2021. The main differences are the occurrence of the flows from Lithuania (indicated with 1), Latvia (indicated by 2), and Egypt (indicated by 3). Furthermore, the increase in migration from Syria (indicated by 7) in 2021.

4.3 Design Goals Fulfillment

Lastly, in this section, I examine whether previously determined design goals from Chapter 3.1 have been fulfilled. This explanation will be based on the example of Austria and the Netherlands, as described in the previous sections. By analyzing the applied methods, I highlight how the design goals were implemented in practice.

4.3.1 Comparability

By using the same layout for each OD map, I made it possible to compare when superimposed (Figure 4.4). Additionally, the movement values for migration flows were encoded in two different ways to further see differences between years and countries. Those encodings included the flow width (the wider, the higher the value) and the color (the more saturated, the higher the value) of each flow. I calculated the encodings so that each of them is comparable over the period (Figure 4.6) and also within the year itself (Figure 4.1 and 4.2). By making it able to compare OD maps with each other, the first requirement is fulfilled.

4.3.2 Interactivity

The physicalization in Figure 4.6 allows for multiple ways to interact with the OD maps. By separating the OD maps from the underlying countries completely and making them two different objects, it is possible to manipulate them to the user's needs. One can juxtapose (Figure 4.3), superimpose (Figure 4.4), or view them individually (Figure 4.1 and 4.2). Furthermore, the physicalization of a space-time cube allows a fixed representation and inspection of patterns over a period. By giving the user the choice of how to interact with this physicalization, the second requirement is accomplished.

4.3.3 Versatility

This approach includes the generation of different European countries based on the user's selection. The processing of the dataset and layout of the OD maps are automated, ensuring consistency across different use cases, for example, Austria (Figure 4.1 and 4.2) or the Netherlands (Figure 4.9). Furthermore, these can be either used to print on overhead transparencies and interacted with tangibly or can be worked with in a digital environment. This approach ensures adaptability, which is suitable for various use cases and fulfills the third design goal.

CHAPTER 5

Discussion & Conclusion

Lastly, I want to give a brief overview of the future work and the limitations of this thesis. I will address the findings and propose potential future improvements. Finally, the chapter concludes with a summary of the main contributions and insights gained.

5.1 Future Work and Limitations

While the physicalization works well for one country, comparing multiple destinations in one STC is currently impossible. Although technically possible, this approach is not particularly practical. That is because the layout algorithm for the maps only takes the corresponding origins of the single destination. Furthermore, if different transparencies of migration maps are stacked, flows and nodes will likely overlap. Some Countries may have a better stacked fitting than others, but the encodings of the flows are calculated for a single destination country within a given period. Migration values from other destination countries are not considered, resulting in not being able to compare flow widths and colors across countries.

Moreover, for some countries, it is difficult to find a proper representation for OD maps. In Croatia, for example, migration primarily happens from neighboring countries. Since Croatia on this scale is represented as very little, those flows can become easily cluttered and unreadable. A possible solution could be to scale the size of the whole map and make those smaller countries appear bigger. On the other hand, incoming flows from faraway countries could disappear.

When the origins of migration flows lie close together and follow a similar direction to the destination, those can get bundled together. These tight spacings around those flows can result in overlaps of flows with flows or nodes, decreasing the readability of the OD map. By moving the origin nodes individually, one can create more space around the flows, further creating a better layout. However, if too many origins share a similar direction, it will only be possible to move them in small amounts.

Lastly, this thesis is based on the dataset, which includes the country of birth of people migrating. However, Eurostat also provides different datasets, including various other fields, which could be interpreted as origins in the context of OD maps. Those include fields like group of citizenship, previous residence, and various combinations. It would be interesting to see visualizations of different datasets for the same country and further examine similarities and differences. Furthermore, how different datasets of migration provide different insights into patterns given over a period.

5.2 Summary

The **research question** I explore is "How can physicalization techniques and space-time cube operations enhance the interpretability of origin-destination maps for migration flows over time?". By integrating these techniques, I was able to visualize migration patterns tangibly and interactively. This can be useful to further explore and analyze temporal patterns. I introduced a new perspective on origin-destination maps over time. The physicalization of a space-time cube in combination with OD maps brings migration visualization into the tangible space. This allows user to explore the topic in new ways by manipulating individual OD maps to their liking, for example, by juxtaposing or superimposing them. These different views can help to gain further insights into migration patterns, whereas physicalization could offer educational and cognitive benefits. Moreover, the straightforward generation of maps makes this project accessible to a wide range of users. As a result, these could contribute to a wide spectrum of fields, such as education, by providing an intuitive and playful way to explore and analyze migration patterns.

List of Figures

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