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Introduction

This work is an attempt to develop an interactive 3D volume map of an archaeological excavation site in a georeferenced 3D space.

The aim is to narrow the gap between two-dimensional representation and three-dimensional measured values in space. Digital 3D volume maps connect digital 3D models with the measurable, cartographic space and thus achieve an enormous boost towards reality. Besides the representation of 3D objects in 3D space, they allow an insight into 3D volume structures like archaeological layers or deposits. Hence, compact information above and below the Earth's surface becomes visible and measurable and can be crosslinked and analysed together. Furthermore, the resulting 3D volume maps can fill the empty space between measured information with continuous probability values in space. Archaeologists thus can be provided with an epistemic tool for better understanding the interactions and relationships of objects in a geodetic 3D spatio-temporal environment.

The study focuses on archaeological stratigraphy. It tries to overcome the so-called 'intra-site GIS-crisis' (Merlo 2016, p. 2) by applying FOSS 3D GIS-modelling and analysis on a micro-scale. Taking into consideration, publications about similar applications in archaeology over the past 10 years, many discussions in this field have occurred (Merlo 2004) but nothing of this kind has been published between my last publication on this topic (2008a) and Merlo's dissertation (2016). Case studies of 'true' (geodetic) 3D mapping from Nigro (2002), Green (2003), Bezzi et al. (2006) and Katsianis (2008), where a full 3D volume object within a 3D coordinate system is created, are discussed in my master's thesis (Lieberwirth 2008b).

Reasons for the 'crisis' might lie in:

- a still small GIS community in 'Digital Archaeology' (DA) which might be deterred from using the non-straightforward application,
- high-performance demands of computer's memory space and graphics cards for solid 3D volumes,
- a focus on large-scale landscape analysis in archaeology, and
- the introduction of 'Virtual Reality' (VR) in archaeology with a focus on architecture in 3D space (Reindel et al., 2016).

The first and second obstacles will be resolved on their own due to general technical developments. The third might be a trend that can change quickly, especially considering the technical advances in the documentation of archaeological excavations. 'Digital excavation' techniques have been improved worldwide not only because high-precision documentation techniques are more available in general but also because of low-price documentation software specially tailored for archaeology (e.g. ArchäoCAD®, TachyCAD Archaeology®).

This study takes up the technical level of my prototype from 2008 (fig. 1.4) for further improvements and a practical test.

The prototype was built from 50-year-old excavation paper drawings of plans and sections of a local (not geodetic) excavation coordinate system. The model can represent solid spatio-temporal phenomena, e.g. the sequences of layer deposition. Archaeological stratigraphy and architecture are represented as voxel geometry volumes which can be clipped in any direction to create digital sections and plans at any place (horizontal, vertical, diagonal). By switching the volumes and layers on and off, a time series of deposition sequences can be animated. Vector, raster and voxel geometry can be depicted at the same time. All vector data can be classified and labelled according to their attributes, e.g. layer number or dating. Raster data can be displayed either with full-scale information or by adjusting thresholds for continuous values (Lieberwirth, 2008a, 2008b).

In contrast to the prototype, this work tries to improve the model in three main parts:

- the model should become a true 3D map by fulfilling all requirements of a cartographic representation (no local coordinate system = research question RQ i),
- the model should be generated from acquired digital excavation data (RQ ii) and
- the 3D environment should provide the same spatio-temporal analysis options as in common 2D GIS (Conolly & Lake, 2006, chap. 8) (RQ iii).

The result should be an analytical 3D volume map in a FOSS GIS-environment. FOSS is chosen to enable further applications and developments of the software in this field.

To solve this task, a conceptual design and operational framework has been developed to serve as the theoretical scope for implementing the working hypotheses concerning data acquisition (chap. 2) and model building (chap. 3).

1.1 3D cartography in archaeology

Cartography deals with areas on the Earth's surface which are described with exact position information (x and y coordinates). Already in the 1970s it became obvious that the definition has to be extended not only contextually but also dimensionally:

> *'The term Cartography is the art, science, and technology of making maps, together with their study as scientific documents and works of art.' (Meynen, 1984). 'In this context, we may regard all types of maps including all plans, charts, and sections, three-dimensional models and globes representing the earth or any celestial body at any scale.' (ICA, 1992).*

This definition includes 2.5D surface maps where the third dimension is expressed via attribute as well as 'true' 3D volume maps. In contrast to 2.5D, 3D maps are represented in 3D coordinate systems with x, y, z-axes which frees up the attribute for other factual information, e.g. non-spatial information like geochemical values or time (Merlo, 2016, p. 12 fig. 2.1.). Technically, an interpolation of these attribute values in 3D space results in a raster volume. As long as such a volume fulfils all requirements of a geographic map, the result can be sorted into the category of 3D cartography (fig. 1.1).

In the context of this work, 3D cartography is meant to model archaeological stratigraphy, deposits, finds and features in a 3D geodetic environment. Since these objects have a three-dimensional volume in reality they are best described as digital volumes in 3D space.

The term '3D map' is mainly used in the context of historical city landscapes and architecture (Picolli, 2018; Reindel et al., 2016). It has often a reference to real geographic positions, e.g. Google Earth© (Google, 2021). However, due to the missing height-axis the third dimension is not measurable in these maps and hence cannot be considered in analysis. From a technical point of view, these models are reconstructions in 3D space. They are hollow objects made of meshes with exact location and a height expressed as attribute placed onto a 2.5D elevation map. The 3D space between and inside these objects is 'empty'. Filling this 'empty' space with information results in a solid volume above or underneath a continuous elevation surface. As long as such a volume has geodetic coordinates, one can call it a 3D volume map (fig. 1.1).

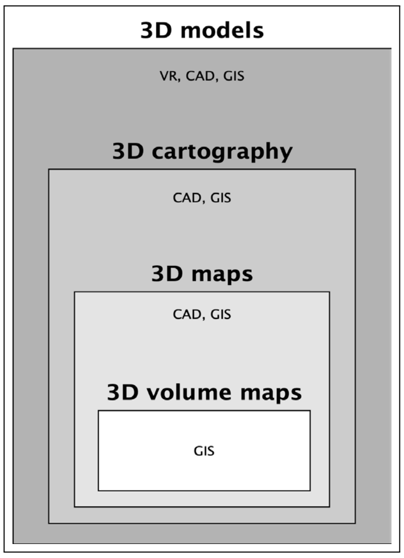

Figure 1.1. Venn diagram of applied DA *termini* in this study.

The most common digital 3D systems in archaeology are CAD-programs and GIS. The first is mainly used for technical vector drawings and drafting in local 2D and 3D coordinate systems. Initially, it was designed for object drawing, replacing technical drawing boards. Recent applications in landscape architecture and urban planning (Akahoshi et al., 2020; Kaden et al., 2020) require the incorporation of geodetic coordinate systems and even limited raster representation (AutoCAD Civil 3D® 2019), but its main emphasis still rests on visualisation and measurement.

In contrast, the focus of GIS is on geodetic coordinate systems with raster calculation, surface visualisation and spatial analysis. Although GIS can also cope with vectors, its main difference to CAD is its analysis function which can combine both raster and vector geometry with geospatial database information. Some can visualise 2.5D raster surfaces by incorporating elevation information in a pseudo 3D space, e.g. ArcGIS 3D Analyst® 2018 and QGIS© 3D Pointscene 2018. At the moment, the only FOSS GIS which provides a complete 3D coordinate system with x, y, z – axes is GRASS 2018a. Therefore, this software is chosen for the modelling and analysis in this study. Further supportive arguments are:

- it belongs to the FOSS community and therefore offers the possibility of repetition, further development and improvement,
- it can handle large data sets (GRASS, 2018a) and
- it can calculate solid volumes as 3D raster cells (voxel-geometry (GRASS, 2018b; Lieberwirth, 2008a, p. 80–81)) in different ways.

Why do archaeologists create maps? *'Maps are graphic representations that facilitate a spatial understanding of things, concepts, conditions, processes, or events in the human world.'* (Harley & Woodward, 1987, p. xvi). A map creates a spatial link between an archaeological structure and its environment by the use of spatial landmarks. This is even true for sketches which were historically the first steps of map creation (e.g. fig. 2.3). The scientific work of an archaeologist as excavator depends on spatial facts explored at archaeological excavations sites or surveys. These facts are the so-called 'first source data' (Conolly & Lake, 2006, p. 61) which has not been altered, edited or undergone a creative filtering or interpretation like written sources or iconography. Hence, archaeologists have used maps to place these archaeological facts as structures in a wider spatial context.

Simultaneously with the development of measurement technology, archaeological equipment has been developed too and is nowadays able to create technical CAD-maps with an accuracy of within a millimetre. CAD-software for documentation is nowadays common on excavation sites worldwide. A major reason for its popularity is its true 3D coordinate environment. Excavators can thus easily discover errors and draw conclusions by switching between various perspectives (from topview to section view and vice versa). CAD describes the real world by using mathematics (vector geometry and linear algebra). With three simple geometric formats (point, line, polygon) former paper-based technical drawings are upgraded by providing:

– interactive access to different kinds of views,
– interactive scaling (zoom in and out),
– precise measurement in true 3D space of the first source data,
– connected attribute information, e.g. via CAD plug-in MonuMap® and TachyCAD Archaeology® or ArchäoCAD®,
– orthophotos, e.g. via CAD plug-in PhoToPlan® and with ArchäoCAD® and
– 3D point cloud objects, e.g. via CAD plug-in PointSense® (PointSense, 2015) or ArchäoCAD®.

The latter can be converted into a continuous mesh surface.

CAD-users can thus get a 3D model of all acquired excavation information. CAD-plans are hence a good basis for 3D modelling in a VR environment. The main application of CAD in archaeology, however, is the creation of technical sections and plans as digital advancement for paper drawings.

To create a map out of these technical drawings is to use a GIS. The interface between both programs and common exchange formats (e.g. via DXF or SHP via TachyCAD®) make a perfect symbiosis. Furthermore GIS offers:

– the combination of maps and drawings from different excavation campaigns in the same area and in a geodetic coordinate system,
– the combination of old paper drawings and modern photographs as long as they have the same coordinates,
– the combination of maps and information from side subjects like environmental science, hydrology, geology etc. and
– the combination of numeric, non-numeric attributes and database content with spatial archaeological information (e.g. non-spatial text descriptions usually handwritten in an excavation notebook).

An additional value is the common GIS-analysis of all data combined together in one system.

Cartography in archaeology can be summarised as the creation of a georeferenced map with archaeological content. Georeferencing in this context means that maps contain position coordinates of a known local, national or world coordinate system. Additional to the archaeological content, these maps are enriched with information from other areas like topography to bring the main topic into a spatial and environmental context. These thematic maps help to understand the wider spatial context of the archaeological structures. In Landscape Archaeology, which deals with the environment around past societies, several spatial analysis methods have been established, e.g. pattern detection (Conolly & Lake, 2006), least-cost path reconstructions (Herzog & Yépez, 2015) and network mapping (Verhagen, 2017) which work fine on large scales (inter-site analysis). In contrast, intra-site analysis works on an excavation scale and therefore addresses other questions (Bevan & Lake, 2013; Blankholm, 1991; Hietala & Larson, 1984; Konsa, 2013). Nevertheless, intra-site analysis can use the same digital environment (GIS) with the same spatial analysis tools (based on descriptive and spatial exploratory analysis) in order to generate fully functional interactive 'archaeological excavation maps' in 2D, 2.5D and 3D.

1.1.1 GIS & space in archaeology

Space in archaeology has always been described with the tools the researcher has at hand. Before the introduction of GIS, archaeologists used cartography or even artificial pictures to demonstrate the spatial relationships of features. Regardless of which method is applied, studying space in archaeology first requires a concept of space.

Archaeologists generally refer to two concepts in this regard (Conolly & Lake, 2006, p. 5).

The first concept deals with measurable information, following the concept of absolute space which requires units of measurement to describe space and was first mentioned by the a Greek mathematician Euclid. Known as Euclid's theorem, it is a basic concept for measurements in 2D and 3D space that remains in use today. The subject was further developed by atomist philosophers in antiquity. Finally, in the seventeenth century, Descartes (1637, p. 297–413) invented the Cartesian coordinate system based on Ptolemy's idea of a grid spanning the globe. This scheme led to the development of accurate 2D and 3D projection systems that remain the basis of cartography today. Finally, Newton's laws of motion, first described in his *Philosophiae Naturalis Principia Mathematica* (Newton, 1687), require an absolute and measurable space as a container for objects within space and time, because – as Newton sees it – objects cannot exist without a spatial relation (an idea that might have its origins in the Greek natural philosophers). This concept is still in use in cartography but not in physics where it was displaced by Einstein's general theory of relativity (Einstein, 1917).

The second concept of relative space (and time) deals with the description of data from a topological perspective. It focuses on the relationships of entities within space, ideas like 'nearby', 'in the direction of', 'between' or 'similar', by using a spatial reference that may differ from a measurable coordinate like travel costs (Barceló & Pallarés, 1998). The concept has been described by philosophers and physicists starting with Galilei, who mentioned a spatial reference or scope for describing the location and movement of objects (Galilei, 1632). Einstein's general theory of relativity continues to provide the basis for describing relative locations (where objects and entities are described according to their spatial relationship to one another).

In addition to their use in GIS, relative space concepts in archaeology are also implemented in the Harris Matrix system (Harris, 1989), for example where the vertical sequence of stratigraphical layers is arranged spatially relative to one another (i.e. 'above', 'underneath') while supporting the temporal interpretation ('simultaneously', 'older', 'younger' etc.).

The two concepts of space are universally applicable in archaeology regardless of periods and places. They are applied in 2D sketches (Nibby, 1819), maps (2.2) and GIS.

An archaeological model tries to reconstruct this sensory environment to test hypotheses of different cognitive perceptions. The challenge of the model is to incorporate all relevant information (Lock, 2003, p. 7 fig. 1.1). But what kind of information is relevant? How do we deal with the incomplete, fuzzy, and subjectively perceived information that is typical of archaeological data?

Perceptions can be distinguished using absolute locations (simply measuring distance and direction) or relative spatial relationships. These scopes can be either spatially explicit where absolute spatial location is essential or implicit, where it is not). Implicit space requires a reference, such as the description of a spatial relationship, whereas explicit implies an exact location. Dealing with space as an attribute is a much more flexible concept for model-building. Relationships can be structured according to their connections, such as a 'one-to-one relationship' or a 'one-to-many relationship' (Stanilov, 2012, p. 255). These relations can be quantitative or qualitative (Gatrell, 1983, chap. 2). The implicit concept is congruent with database design, where both types of relationships can be modelled with identifiers as connectors. This explains why the incorporation of the theoretical concept into a geodatabase is implemented in Geographic Information Systems (Parker et al., 2003). Furthermore, we can choose between isotropic (directional independency) and anisotropic (directional dependency) approaches in GIS. These are mainly incorporated and used in such procedures as cost-surface analysis (Conolly & Lake, 2006, p. 215), where archaeologists can analyse economic routes from A to B or investigate easily accessible areas around a central point. Perceptions are generally scale-dependent. The impression of an area or environment might differ strongly with the change of scale: it matters greatly if an area is perceived either from a bird's-eye view or on foot, for example, or by a static watchman or a dynamic horseman, since the scale for the latter might change over time. The perspective of a researcher working with cartographic material might give a useful overview, but this is generally not the way that past societies viewed their environments. The representation of scale must be acknowledged from two perspectives: the past community's view and the analyst's view. The applied analysis should therefore be executed as a multi-scale analysis. The applied scale also has an impact on the resolution of the model (its level of detail), however, and should therefore be acknowledged during the model-building process (Romanowska, 2015, p. 10 fig. 2). The next steps require a transformation of the scope descriptors into the language of the GIS-system to obtain an analytical unit. As long as such descriptors have a location and can be expressed quantitatively, they can be incorporated into GIS.

The purpose of Geographic Information Systems for archaeology is to capture, store, compute, analyse, and present spatial data and their relationships. These functions can be assembled in five processes: data acquisition, spatial data management, database management, data visualization, and spatial analysis (Conolly & Lake, 2006, p. 11). Depending on the intended use, the result can be a map, model, table, or statistical value. GIS needs location information to describe the objects under examination, as well as an attribute for those objects. For the graphical description, GIS uses two data formats: the vector format and the raster format. The first works based on analytical geometry to describe objects like points, lines, and polygons in a defined space. The raster format is used for continuous data (a detailed description of GIS-data models can be found in any GIS-handbook). The voxel format used in this study can be understood as an extended raster in the third dimension by keeping the same properties. The first type can be attached with attributes from a table or a database system. This connection – the combination of spatial information with attributes, called a geodatabase – is what makes GIS so powerful. Attributes without an explicit location, on the other hand, can be depicted with the second format type, the raster format. This format type can hold only one attribute spread over a defined, square-shaped space (Conolly & Lake, 2006, chap. 2.4.2). The size of the square, pixel or voxel can vary between the layers, which makes it possible to adjust the resolution of the model according to the background knowledge and level of detail one would like to reach. The latter is more of a conceptual than a technical issue. From a technical point of view, there is no limitation on detail (a topic that refers to fractal geometry, Mandelbrot 1982, chap. II). Nevertheless, what kind of detail is necessary depends on the concept and research question and gives the user opportunities for modelling fuzzy information where location is only described as a spatial reference. Both types (raster and vector formats) consist of a unique location within a defined space so they can provide absolute distances according to either Euclidean geometry or surface distances and topological information. With these possibilities at hand, archaeological GIS users are able to create a digital model of the real world (Conolly & Lake, 2006, p. 4). Furthermore, three data formats allow the flexible application of the two concepts of space (1.1). GIS might not be a high-end technology from a technical perspective but it gives the archaeologist opportunities to create a meaningful, analysable model of an archaeological site (Wheatley, 2004, p. 3).

1.1.2 3D models in 3D space

According to Stachowiak, a model is characterized by at least three features:

1. *A model is always a model of something – a reflection or representation of a natural or an artificial original, and this original itself can be a model in turn.*
2. *A model generally does not capture all the attributes of the original, but only those that appear relevant to the model creator or model user.*
3. *Models are not clearly assigned to their originals. They fulfil their replacement function*
   a) *for certain subjects (for whom),*
   b) *within certain time intervals (when) and*
   c) *they are restricted to certain mental or actual operations (for what).* (Stachowiak, 1973, p. 131–133).

The best case scenario would be that the extension, realm, distortion and quality of a model is outlined. The crucial point in archaeological model building is its verification. Archaeological documentation is based on a 'macroscopic anatomy' of the excavated objects. In other words, we can only document what we see. This is also described as 'human conceptualisation of reality' (Peuquet, 1984, p. 67). However, optical conditions change even during one day. What we have seen in the morning might have vanished by the afternoon. Hence, there will always be an open question as to whether everything vital was seen, recognised, identified and finally documented. Furthermore, we never know how much we missed.

Models are a simplification of the real world (Orton, 1980) and always imperfect (Ervin & Hasbrouck, 2001, p. 4). So why model if we never meet reality?

The creation of a model gives us the opportunity to focus on certain aspects of a complex system. An abstraction can make complex relationships more coherent. Models are the basis for further analysis in mathematics, statistics (Orton, 1980), diagrammatic reasoning, etc. (Romanowska, 2015, p. 27). In other words, a model can act as a link between theory and the real world (Orton, 2000).

The first step in working with GIS is to create a model, a process through which real-world information is transformed into a digital, quantitative GIS-environment. This quantification of archaeological facts in general is not new. Since the beginning of archaeology, tables and catalogues have been used to structure and categorize high amounts of data (Petrie 1899, Foucault 1966, p. 143). These structures now form the basis for databases and further analysis (Orton, 1980). Today GIS offers the opportunity to bring together all spatial, quantified information in one system with the option of further analysis even in 3D cartography.

As in statistics, one of the first steps during the conceptual phase (Romanowska, 2015, p. 10 fig. 2 'the model development sequence, step 3') is to make decisions about the selection of data that will be used for model-building. The model ultimately represents the sample population. It is the general pool of data for further analysis. Hence, what kind of data we choose and how we depict them in GIS is a sensitive point in GIS-analysis because all further work refers back to this data selection.

In archaeology, the very first selection of data is made during excavation, when one decides what kind of data is to be documented and in what resolution. The choices made here depend on archaeological expertise, applied measurement methods, and survey devices. This data pool should be used for a second selection that considers the research question and the suitability of the data to be included into the GIS-system. Transformation and calculation processes for model-building might incorporate further data transformation, smoothing, oversimplification or alteration of the legacy data by interpolation or extrapolation algorithms to generate probability values at places where no legacy data exist. The vectorization of raster data sets (like photographs or scanned excavation plans) can create precise borders that were originally fuzzy and vice versa. Since the aim of the process is to create a meaningful model, however, these processes might be acknowledged as formation processes for obtaining a suitable basis for analysis, experiments, and scenarios. As Lock points out, creating a model is often the only way of dealing with archaeological data that have been subjected to similar site formation processes (Lock, 2003, p. 147).

In each case, the excavated archaeological material must be transformed into a document readable by either human or machine. By this point decisions have already been made about the clearness of borders, middle points of objects, transition areas, etc. As mentioned above, it is possible to incorporate these interpretations in the GIS because the transformation has been already done in the scientist's mind. The potential of GIS means that it can combine different information in one system to facilitate new views of the data. This perspective may be more complex than that at the excavation or survey itself. The changed perception begins at the moment of data collection, which is already selective.

How accurate is the model? The application of statistical and quantitative methods to archaeology proved reliable even before the introduction of GIS (Baxter 2003, Orton 2000). If the aforementioned considerations about statistical bias are kept in mind, GIS remains a useful analysis tool and makes it possible to use statistical verification methods, significance testing, and hypothesis testing.

Verification is a guarantee of quality. This step comes right after the creation of the model and has to be included in the methodological circle (Romanowska 2015, p. 10 fig. 2, Breitenecker et al. 2015, Brughmans et al. 2014, p. 445).

Most common statistical verification methods nowadays comprise an integral part of certain types of GIS-software packages like significance testing of parameters with parametric or non-parametric tests for large or small sample sizes, robustness tests performed on models using hypothesis testing such as the chi-square test and the *Mann-Whitney U test*, and inferential statistics for investigating the relationship between two or more variables (Hodder 1986, p. 14, Lock 2003, p. 2,118,125 infobox 5, Lieberwirth et al. 2015).

But how do we verify an incomplete model? One possible solution might come from other subjects and applications in archaeology which deal with discrepancies by keeping models as simple and as abstract as possible and focusing only on certain aspects (Brughmans et al. 2014, p. 446, Romanowska 2015, p. 25, Lock 2003, p. 148). If a model theory can be tested under controlled conditions, there are more facts than hypotheses (Heppenstall et al., 2012, p. 740).

Translated into a more abstract model of mathematical set theory, where M_r represents the summary of all real world data (M stands for amount, r for reality) and M_m represents the amount of modelled data (m stands for model, a subset of all real data), one could say:

$$M_r = \{A \subseteq M_r, B \subseteq M_r, C \subseteq M_r, D \subseteq M_r, \infty \subseteq M_r, E = M_r \subseteq M_m\}, E > 0 \quad (1.1)$$

where

$$M_m = \{A \subseteq M_r, B \subseteq M_r, C \subseteq M_r, D \subseteq M_r\} \quad (1.2)$$

and

$$M_m = M_r \setminus E = \{x \mid x \in M_r \wedge x \notin E\}$$

see fig. 1.2.

The amount of the unknown E, the missing information of a model M_m, will never be *zero* but we can try to come as close as possible. This exactly is the aim of this study – to minimise E with the hybrid approach of combining information from different subjects to model the same object.

The conceptual design considers three perspectives:

– a content perspective,
– an external design requirements perspective and
– a structural perspective.

In contrast to Merlo (2016, p. 70 fig. 5.1) the content perspective in this study aims to acquire as much data as possible, disregarding the current research question. The idea behind this is on, one hand, to minimise E, while on the other hand to be aware of as much information as possible from a process which can never be repeated. The challenge in modelling is to find an optimal way to transcribe the perceived and measured information into something readable and storable.

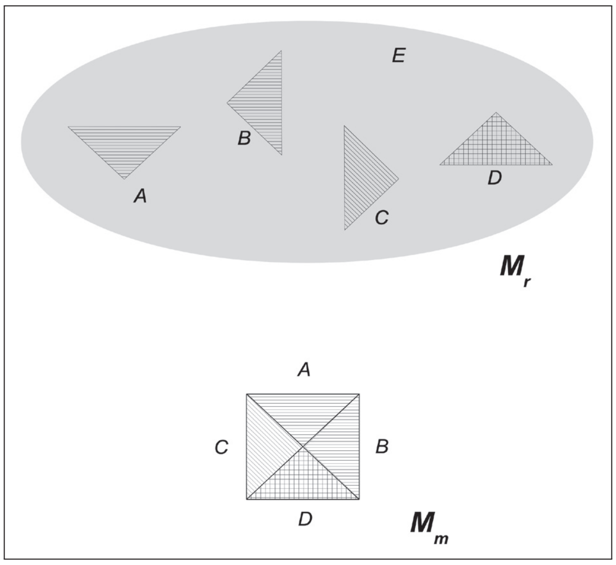

Figure 1.2. Graphical representation of formulas 1.1 and 1.2.

Filter 1, displayed by A, B, C, D in the formula (fig. 1.2), represents the process of documenting at a site. With different measurement techniques and sensors it is possible to reduce the unknown amount of E within the total amount of M_r.

In the modelling process, the second step (filter 2) one has to find an ideal reconstruction environment that will not minimise the already reduced amount of M_m left after the first operation (fig. 1.3).

The third step includes the structural perspective. Its aim is to find an optimal environment for managing, storing and analysing the model's information to produce the best possible harvest from the legacy data. The challenge here is to find the most suitable model from all the acquired data relevant to the analysis (Stachowiak, 1973, category 2).

A solution can be found by the computational perspective which takes into account these external design requirements. This approach can be seen as a combination of the two perspectives described above.

Besides concrete and mathematical models, computational models form a separate class of models for simulations. Weisberg (2013) describes the computational environment like a laboratory, a sterilised space that helps to focus on the object of interest.

This perspective includes already the acceptance of simplification which has been discussed in recent studies as one of the most feasible solution for simulating complex societies. According to Stachowiak's category 3 (1973), Romanowska (2015) and Deng (2001), this concept of

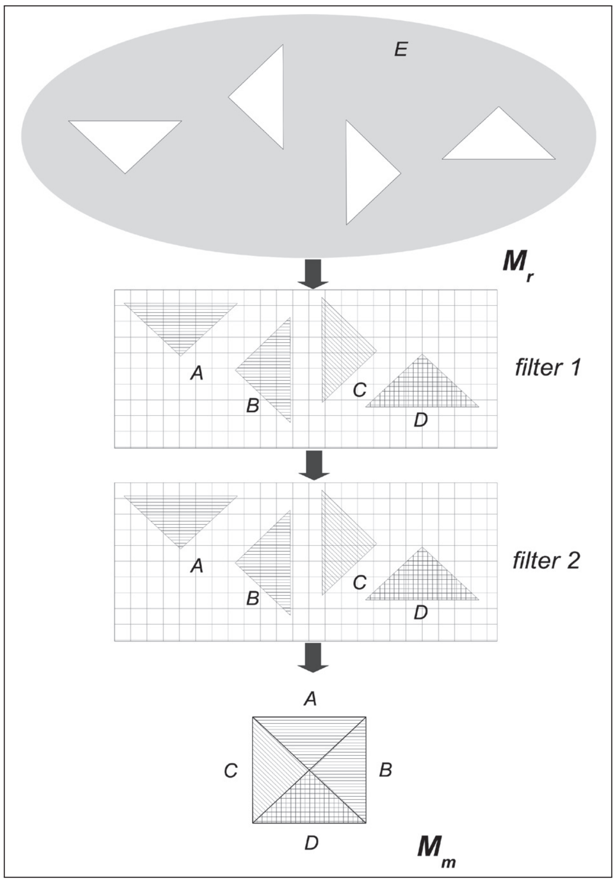

Figure 1.3. Graphical representation of formulas 1.1 and 1.2 with filters.

'constraint data models' helps to focus on certain aspects better than trying the impossible task of creating a second real world (Kowarik et al., 2015).

Archaeological 3D models (fig. 1.1) have their origins either in CAD with a defined coordinate system or in a graphical VR environment with a local (inherent in the system) coordinate system (Landeschi et al. 2015, Paliou 2013, fig. 5.6b, Soler et al. 2017). All three systems, GIS, CAD and VR, have their similarities and overlaps but can be distinguished on the basis of their priorities:

– spatial analysis for GIS,
– focus on measurement in CAD and
– reconstruction in VR.

According to the aims of this study, the resulting 3D model has to be available for spatial intra-site analysis. Hence, GIS as the 'system of choice' seems to be the best environment for the task in this study.

The most complex 3D format of a 3D model in a digital 3D space is the 3D volume map – 'the format of choice' for this study. It fulfils all requirements of a 3D model, can be displayed as VR but can be also be calculated in GIS (1.1). The main distinctions between VR and GIS models are:

– VR does not necessarily have a reference to a geographic location,
– VR cannot handle solid volume information underneath a 2.5D map for a quantified exploration and
– only GIS has (so far) the possibility of spatial analysis.

CAD environments are, according to their functionality, much closer to GIS than VR. The two main distinctions between CAD- and GIS-models are:

– CAD cannot handle the solid volume information and
– CAD has limited spatial analysis functionality.

To summarise, a 3D GIS-volume map can be a VR model in a 3D space (1.1) but a 3D VR model cannot be a 3D map because it might lack geographic information. A CAD-system cannot (yet) depict a 3D GIS-volume map (fig. 1.1).

All three 3D models systems, GIS, CAD and VR, are acting in 3D space and are a simplified reflection of reality. CAD and VR follow the concept of a so-called 'spaghetti model' (wire-frame model) (Laurini & Thompson, 1992, p. 399–425). GIS, on the other hand, can also include the concept of the 'pizza model' (concept for areas and volumes) (Laurini & Thompson, 1992, p. 426–443). Since this study focuses on archaeological excavation models, simplification is not the first aim of archaeological modelling here – rather the opposite. In general, an archaeological record is rare and therefore precious to archaeologists who try to collect and document as much as they can, because after the excavation the whole structure is vanished and the process cannot be repeated. The scientific model building in this study follows a similar strategy best described as the concept of 'constraint data modelling' (Deng & Revesz, 2001). At first, a model will be built from all available information of the site. Only in a second step will the model be reduced according to the research question under analysis. The best situation for this deliberate model reduction would be to know what and how much is left out.

1.2 Conceptual design & operational framework

The prototype from my master's thesis (2008, fig. 1.4) serves as a starting point for further development.

In contrast to the previous model, the result of this study should be further developed towards an interactive, archaeological, digital 3D volume map (RQ iv). To meet this goal, a conceptional design has been developed and implemented into the operational framework of this study.

From a methodological standpoint, the three main working steps of data acquisition (excavation), data modelling and data analysis have to be carried out (fig. 1.5). However, one must bear in mind that the requirements of the analysis software influence the previous working steps in terms of data format, respectively hardware and software. Therefore, the conceptual design process must follow the working step process vice versa.

In order to approach the research aims of this study, demonstrations in section 1.1 show what kind of concepts

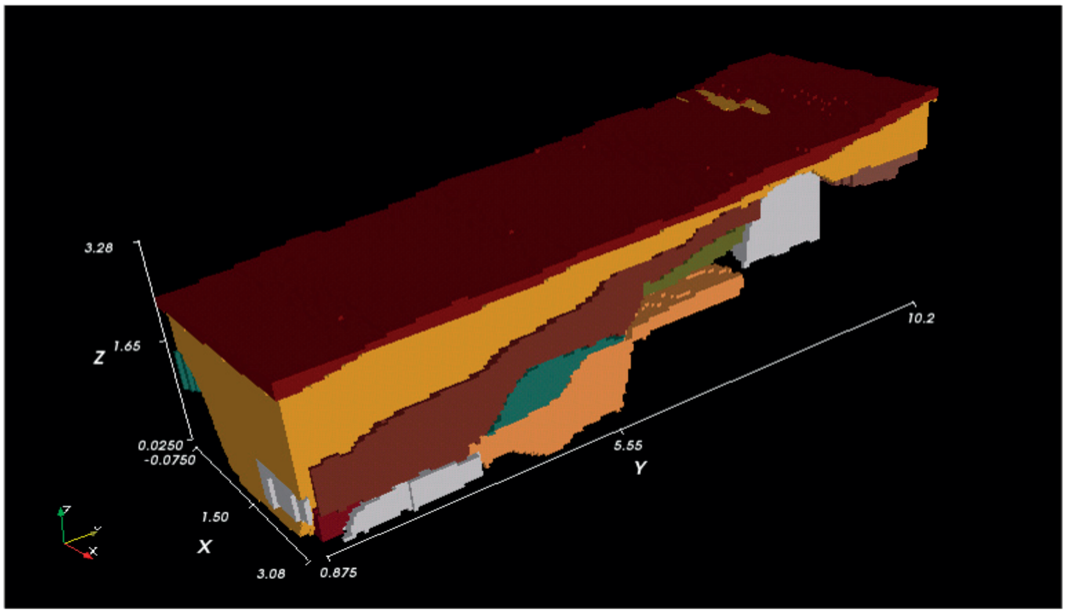

Figure 1.4. Prototype, reconstruction of excavation trench ix at the site of Akroterion at Kastri in Kythera/Greece (Reproduced of U. Lieberwirth, 2008a, fig. 14).

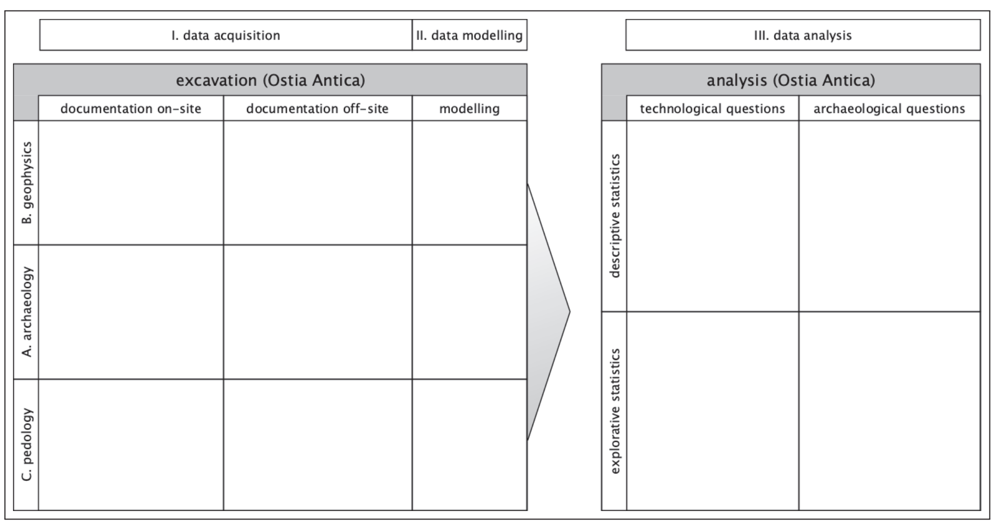

Figure 1.5. Process chain of conceptual design.

might be most suitable. It is preferable to minimise platform and system changes in order to save time and money and to avoid data exchange errors (RQ v). Finally, the needs and requirements of the platform will specify the operational framework for the data documentation. The detailed description of the methodological concept of this study is outlined in subsections 1.2.1, 1.2.2, 1.2.3.

Concerning the research aims, which include low costs and open code for the applied software, the only Free and Open Source Software (FOSS) which can calculate and manage 3D volumes in a true 3D coordinate system is GRASS. It was used successfully to develop the prototype (fig. 1.4), and, with no alternative software available, is ideal for this study. Additionally, this software meets the methodological requirements.

The concept of this study is to overcome the discrepancy between reality and model by minimising *E* (fig. 1.2).

One part of the solution was to integrate 3D geophysical measurements. Geophysics is generally used before an excavation starts in order to select the most interesting archaeological spots (visible as geophysical anomalies) as a kind of prediction. However, the results can also serve as a verification system in the post-excavation process.

Hitherto, geophysical results are used as two-dimensional pictures. They generally come as georeferenced images, so-called 'time slices' of different depths. GPR wavelengths are recorded in 3D space (Biel & Klonk, 1994, chap. 27.1.8) and therefore are available for the whole excavation trench volume. Hence, in this study the question arose: why not reconstruct this record completely as a 3D volume structure?

The same method could be applied by using geochemical information from an archaeological trench. Soil samples are usually taken on top of an archaeological stratum, e.g.

to differentiate working and living zones inside a building or area (Biel and Klonk 1994, chap. 7.1, Brandt et al. 1992, Lloyd and Atkinson 2004, Salisbury 2013). We took soil samples of the whole trench as punctual information, disregarding strata borders. In this study, I wanted to go a step further and extend these distribution maps into the third dimension. The aim were to visualise geochemical volumes in order to find new strata (from a geochemical perspective), to confirm archaeological layer borders in 3D and finally to minimize *E*.

1.2.1 Data analysis – a methodological & archaeological approach

GRASS, the chosen modelling software, calculates solid volumes inside a geodetic 3D coordinate system. Alternative FOSS GIS-software programs like QGIS (2018) and gvSIG (2018) are currently only able to deal with 2.5D raster surfaces and vector data. The GRASS GUI (graphical user interface) accelerates the calculation process, which is one reason for the flexible management of large data sets like 3D point clouds, the main format in this study. This effect is supported by the software's module structure with, for example, a separate viewer window which can be switched off during RAM-consuming processes for calculating volumes. The same is true for the 3D analysis processes. They were executed either in GRASS or via FOSS ParaView© (2016). The latter is a scientific graphical viewer enriched with analysis functions and filters in 3D. It is recommended by the GRASS community when it comes to its visualisation limits. As well the viewer offers several 3D analysis tools and filters (Ayachit 2018, chap. 3–6, Lieberwirth 2008a).

From an archaeological perspective, this study aims to incorporate all documented information (including the geophysical and geochemical) from the excavation site into GRASS, respectively, ParaView© for analysing. The study tries to prove that an accurate 3D model of an archaeological excavation site cannot only include all data but can also be used as a basis for spatial 3D analysis. With the combination of different parameters and the application of statistical tools it should be possible to calculate and export new data out of the imported. The aim is to create a digital 3D GIS-model of the excavation trench. It should not only visualise surfaces, features and finds but also archaeological stratigraphy as solid 3D volume objects (RQ vi).

From an archaeological point-of-view, the following questions should be answered by this study (RQ vii):

- Is it possible to extract archaeological stratigraphical borders out of the geophysical record?
- Is it possible to extract archaeological stratigraphical borders out of laser scan RGB-values?
- Is it possible to extract archaeological stratigraphical borders out of the geochemical (pedological) record?
- Are the 3D borders of archaeological strata, geophysical strata and geochemical strata congruent?
- Are the concentration centres of archaeological, geophysical and geochemical anomalies and their statistical outliers congruent?

Finally, with the combination of data from these three subjects (geophysics, pedology and archaeology) the following questions arise:

- Can we recognise the same structures with different methods?
- Can different methods act as verification for each other? and
- Does this mean we can get reasonable results with just one method?

From a methodological point-of-view, the analysis of the 3D volume model should enable the user to (RQ viii) include all quantified information and combine them to thematic multi-scale 3D maps, which:

- can be statistically analysed in 3D space,
- are as precise as the documentation data and
- extend the analysis into the fourth dimension.

1.2.2 Data modelling – a methodological approach

The 3D model and data should be as objective as possible to get a model as close as possible to the real world. The aim of the modelling working step is to reconstruct the site as it was at the time of the excavation as a basis for spatial analysis.

In comparison to the 2008 prototype (Lieberwirth, 2008a), this model will be enriched with data from the side subjects geophysics and pedology. For this aim, these data need to be in a numeric format, in the same coordinate system and with the same resolution as the archaeological record.

The chosen GIS-environment for modelling offers the data format voxel (volume pixel) for solid volume calculation. This format was successfully tested with the first prototype to calculate archaeological deposits (Lieberwirth, 2008a). According to the conceptual framework conditions of this study I am limited to the available solid modelling concepts of GRASS although there are alternative technical solutions available (Merlo, 2016, p. 44 tab.3.2). At the moment, there are five modules for voxel generation available (https://grass.osgeo.org/grass74/manuals/raster3dintro.html):

i) *v.to.rast3* (detailed description: https://grass.osgeo.org/grass74/manuals/v.to.rast3.html), which generates just one voxel around the original 3D point,
ii) *r.to.rast3elev* (detailed description: https://grass.osgeo.org/grass74/manuals/r.to.rast3elev.html), which generates a cube or cuboid of the defined 3D region out of raster surfaces via extrusion,
iii) *r.to.rast3* (detailed description: https://grass.osgeo.org/grass74/manuals/r.to.rast3.html), which performs just like r.to.rast3elev,

iv) *v.vol.rst* (detailed description: https://grass.osgeo.org/grass74/manuals/v.vol.rst.html), which provides the only interpolation algorithm in 3D space and
v) *r.vol.dem* (detailed description: https://grass.osgeo.org/grass74/manuals/addons/r.vol.dem.html), which uses extrusion of raster data between two raster surfaces.

According to the requirements and outputs of the modules, only options iv) and v) are useful in this study because v.vol.rst uses only probability statistics and r.vol.dem can outline the calculated result with reasonable borders in 3D space.

For iv) the input data need to be a 3D vector point cloud. The algorithm is a 3D interpolation of a so-called *w-value*. This value has to be a numeric attribute which can be any kind of quantitative information like geochemical or geophysical values. The *z-value* needs to be a real coordinate. Voxel creation via interpolation can be understood like the creation of continuous raster surfaces in 3D. The result is a continuous volume with fuzzy borders of adjustable threshold intervals. This calculation process is hence very suitable for measured values in 3D space.

Geophysical and geochemical information is, in comparison to archaeological, measurable information. This is seen as a great advantage against archaeological deposits in this study because the course of archaeological structures is determined by the excavator's decision only. The archaeological question here is, whether the geophysical or geochemical information shows the same course and borders as the archaeological. If this question can be answered positively, there might be a way to predict archaeological remains without excavating by using geophysics and geochemistry (RQ ix).

For v) raster surfaces need to be extruded in an up or down direction.

This GRASS module is chosen for calculating non-numerical archaeological volumes. The challenge in building a digital model out of the archaeological record is the transformation of archaeological interpretations into numerical data.

1.2.3 Data acquistion – an archaeological & methodological approach

Archaeological excavation documentation depends on measurement. To describe objects and their place of discovery, we need to assign their precise location in all three dimensions. The archaeological challenge of this working step in this study is transforming real objects (archaeological remains like finds, features and stratigraphy) into a computer readable format. The reality has been transformed into this frame. As demonstrated before, the analysis method dictates the data format for acquisition. The data documentation is the working step between physical excavation and modelling. Hence, considerations have to be made before going into the field: what kind of documentation hardware and software should be applied and how can the objects be described in an efficient way at excavation and in a suitable way for later analysis, respectively. To avoid unnecessary working steps, the ideal documentation system should already generate the final data format (RQ xi).

Consequently, since the analysis software has already been chosen, the data acquisition has to be in a GIS-readable format. Hence, the use of digital devices which produce 3D vector data is preferred. The final concept for the operational framework of the digital excavation, which acts as a testing ground in this study, is described in detail in tables 1.1, 1.2, 1.3. In this study, the ideal data type for documentation would be a format readable by GRASS, or at least in a GIS in general. The same is true for documentation software solutions. The less programs are needed, the less working steps have to be executed. This helps to avoid data transformation and conversion which might produce errors and distortions (RQ xii). The integration of additional information from two side subjects is a further challenge.

Geophysical data and the pedological data should produce similar data types as preferred over the archaeological.

In summary, the excavator is confronted with the challenge of transforming the real world into a digital model. During acquisition a solution has to be found for:

- What kind of information we want to depict and how much of it to model,
- What vector type (point, line, polygone) to use and
- How the data are to be acquired?

Geophysical investigation in archaeology belongs to non-destructive excavation methods. Its integration into the excavation process allows for precise planning in horizontal space. In this study, the third dimension of these data should be integrated, unlike the common application of 2D picture output, making it possible to plan the excavation more precisely even in a vertical direction (Gaffney et al. 2013; Sarris et al. 2018).

In this study, we take advantage of recent developments in sensor devices. It is assumed that due to more precise non-destructive insight possibilities underneath the surface at a significant depth, it is possible to recognise stratigraphical differences. It is therefore hoped that it is possible to find stratigraphical borders with geophysical support in three dimensions.

The same experiment is planned with geochemical data. In pedology, soil strata can be differentiated by their chemical compounds (Salisbury, 2013; Sarris et al., 2018). The idea of this study is to measure the chemical soil composition in 3D space. The result should be a 3D volume model in the same coordinate system and resolution as

Table 1.1. Archaeological working hypothesis: documentation of archaeological information

A. archaeology

	i) Record Type	ii) Data Format	iii) Hardware	Software
archaeological surfaces	course of archaeological strata	- 3D point cloud (multipoint)	- TLS - total station	CAD
archaeological features	location & size of features, feature context	- 3D polyline (vector line)	- total station	CAD
archaeological finds	location & size of features, feature context	- 3D point (vector point)	- total station	CAD

Table 1.2. Geophysical working hypothesis: documentation of geophysical information

B. geophysics

	i) Record Type	ii) Data Format	iii) Hardware	Software
geophysical anomalies	course & depth of geophysical strata & features	- GPR wavelengths	- GPR	ParaView©

Table 1.3. Geochemical working hypothesis: documentation of pedological information

C. pedology

	i) Record Type	ii) Data Format	iii) Hardware	Software
geochemical anomalies	course & depth of geochemical strata & features	- 3D point (vector point)	- total station	CAD

the archaeological and the geophysical models for further comparison.

For this reason, a probabilistic soil sampling procedure is planned by using a three-dimensional regular grid inside the excavation trench in order to obtain unbiased 3D raster information (Orton, 2000).

The practical implementation of the operational framework described above is executed in *Ostia Antica* at the Main Forum's West Porticus' archaeological excavation with trench 1. An introduction into the archaeological site follows in section 2.1.1.

1.3 Structure of this book

This publication is divided into two parts, a text book and for the sake of the third dimension, supplemented animated images and video.

It starts with a theoretical introduction into the topic of 3D cartography in archaeology and its application in this study. The following three chapters deal with the practical implementations. They describe the data acquisition, the modelling process and finally the analysis process of the model.

The last chapter discusses and summarises the results of the practical tests compared to the theoretical conceptual framework. They close with an outlook for future studies.

1.3.1 Chapter 1: Introduction

The chapter introduces the reader into the scope and intention of the monograph. It is presumed that readers have a background knowledge of GIS-applications in archaeology. The introduction starts with cartographic work in archaeology in general with a focus on 3D modelling.

It follows the conceptual design of the three main working steps of this study: data acquisition (chap. 2), data modelling (chap. 3) and data analysis (chap. 4). The chapter introduces the test setup and the operational framework tailored for the purpose in this work. According to these working hypotheses research aims and questions RQs are formulated. The latter are structured with a Roman numeral system.

The road to these destinations including all side streets and dead ends is described in the following chapters.

1.3.2 Chapter 2: 3D data acquisition

After an introduction to the experimental site at *Ostia Antica* the chapter presents the practical implementation of the methodology concerning 3D data acquisition. It contains a detailed description of all data acquisition processes on-site categorised under the subjects geophysics, archaeology and pedology. Finally, it describes the data management structure after the excavation as a off-site process.

For a better overview, working step sequences (WS) follow a Roman numeral system which is used throughout the monograph and appears also in processing chain charts which are displayed in chronological order including the applied hardware and software. Detailed descriptions of each working step can be found in tables by using the same numerical system for cross-referencing.

1.3.3 Chapter 3: 3D data modelling

The modelling chapter starts with the import of all acquired data into the chosen GIS-environment and ends with the export into a ParaView©-readable format, the viewer of GRASS GIS.

In between, one can find detailed descriptions of the workflows for each data type for generating the final 3D GIS-model. Again, the working steps are summarised in process chain charts and described in detail in tables with the same numerical system used in chapter 2.

1.3.4 Chapter 4: 3D data analysis

The analysis chapter starts with the import of all data from chapter 3 into the main analysis software ParaView©. The chapter is subdivided into different analysis approaches which try to answer the research questions from chapter 1.

1.3.5 Chapter 5: Discussion & conclusion

The analysis results and working steps are discussed and summarised in this chapter by taking up the same structure and numbering as above. It consists of comments about advantages and disadvantages (discussion), final results (conclusion) and suggestions for future applications (outlook).

Finally, all research questions (RQs) from chapter 1 and 2 are taken up and answered.