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Report on how to optimise speed in the 'CT Pipeline'

Report for:

EMPIR project "17IND08 AdvanCT - Advance Computed Tomography for dimensional and surface measurements in industry"

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1. Objective

This report fulfils activity 5.3.7 of the EMPIR project "17IND08 AdvanCT - Advance Computed Tomography for dimensional and surface measurements in industry". To support dimensional metrology in advanced manufacturing in the future, the project will develop traceable CT measurement techniques for dimensions and surface texture. Open issues regarding traceability, measurement uncertainty, sufficient precision/accuracy, scanning time, multi-material, surface form and roughness, suitable reference standards, and simulation techniques will be addressed through the project's objectives.

The work described in this document is related to the issue "sufficient precision/accuracy vs scanning time". DTI, in collaboration with Novo Nordisk and Volume Graphics, will evaluate how to optimise speed in the 'CT Pipeline' (the different tasks and steps which make up dimensional measurements using CT) in an industrial setup. The intention is to write a report on where to focus effort to make the process faster under certain assumptions and requests. This report will be disseminated via the project website and it will be made available to the partners via a presentation at a project meeting.

2. CT pipeline

The process - from the moment a measuring job is received to the moment the results are handed over - was mapped in the following so-called "CT pipeline" – the different tasks and steps which make up dimensional measurements using CT.

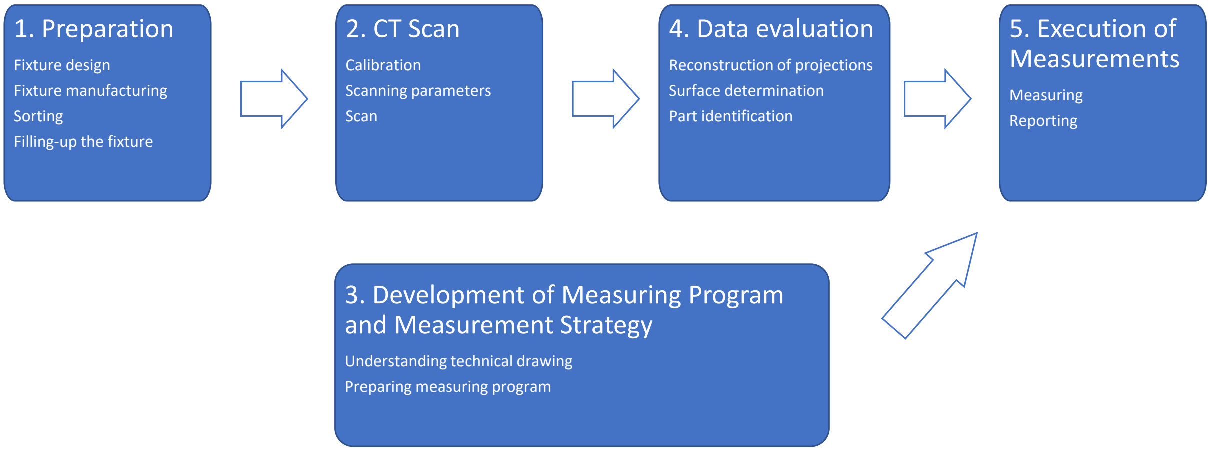


Figure 1: CT pipeline - the different tasks and steps which make up dimensional measurements using CT.

The 5 main steps that characterize the CT pipeline are shown in Figure 1 and are described here below:

1. Preparation phase which consists of:
    - Designing a fixture to hold the parts to be CT scanned
    - Manufacturing of the fixture
    - Sorting of the elements (if there are more than 1 part to scan)
    - Filling-up the fixture
2. CT scan phase which consists of:
    - Calibration of the CT scanner
    - Setting the scanning parameters
    - Performing a CT scan
3. Development of the measuring program and the measurement strategy which consists of:
    - Understanding of the technical drawing
    - Preparation of the measuring program
4. Data evaluation phase which consists of:
    - Reconstruction of the scan projection
    - Surface determination
    - Part identification
5. Execution of measurements which consists of:
    - Measurement analysis – execution of the measuring program
    - Reporting the results

The 5 steps described above were timed throughout a case study provided by Novo Nordisk, see chapter 3. The different CT-pipeline phases were carried out by:

1. DTI
2. DTI and Novo Nordisk
3. DTI, Novo Nordisk and Volume Graphics
4. DTI, Novo Nordisk and Volume Graphics
5. DTI, Novo Nordisk and Volume Graphics

Using the available CT systems and software at the different sites during year 2020. The results are presented and discussed in chapter 4.

3. Case study

Novo Nordisk provided 25 demo parts to carry out the experimental investigation. The part is illustrated in Figure 2 and the relative measurands are listed in Table 1.

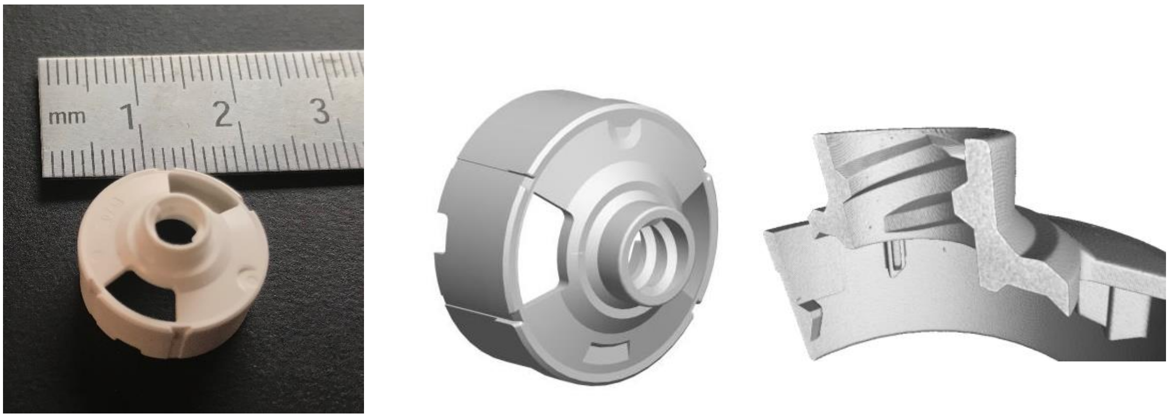


Figure 2: Demo part provided by Novo Nordisk to carry out the experimental investigation.

Measurand	Nominal value	Description
M1	16.395 mm	Diameter (Datum P); Tol ± 0.2 mm
M2	3.9 mm	Distance; Tol ± 0.2 mm
M3	0.1 mm	Parallelism
M4	0.4 mm	Surface form deviation
M5	60°	Angle between symmetry of 2 grooves; Tol ± 0.5°
M6	0.85 mm	Groove width; Tol ± 0.2 mm

Table 1: Measurands of the demo part

Two case studies were carried out: 1 scan containing all the 25 parts and 5 scans containing 5 parts per scan. The reason is to perform two investigations which simulate a high-resolution scan and a low-resolution scan.

4. Results

4.1. Preparation phase

During the preparation phase a fixture was designed and manufactured in order to hold the 25 Novo parts while they are scanned.
Several factors were considered during the design phase of the fixture:

- How many parts do we want to scan in one time?
- Which is the best possible way to hold the items so that the fixture is easy to use?
- What is the voxel size we want to achieve in the scan?
- How stable is the fixture?
- How to design the fixture so that the part is not pressed in critical areas?
- How to design the fixture so that the part is not hold in areas that need to be measured?
- What is the optimal angle of the fixture so that the part can have the best orientation while it is scanned?

Taking into account all the above points, the fixture was designed having a main tower with 5 layers. Each layer has place for 5 items. In this way it was possible to easily carry out the 2 investigations (1 scan with 25 parts and 5 scans with 5 parts in each scan).

The fixture was manufactured in extruded polystyrene since it is an extremely strong material which absorbs a minimum of water, has a long service life and is easy to handle. At the same time, it is an extremely lightweight material thus it does not interfere with the material of the Novo parts (ABS) in the grayscale graph.

The fixture is illustrated in Figure 3 and Table 2 summarizes the time spent in each step of the preparation phase.

Figure 3: Fixture set-up.

Preparation phase	Time [min]
Fixture design	360
Fixture manufacturing (made of 16 parts)	660
Sorting	15
Filling-up the fixture	15

Table 2: Time spent for each step of the preparation phase.

4.2. CT scan phase

The timing for the preparation of the scanning parameters and the CT scan itself is reported in Table 3. Two observations have to be made:

- Calibration task is not considered since it is performed once or twice a year, therefore it is not dependent on a specific case study.
- The task "CT scan" is divided in:
  - 1 scan with 25 parts which is called "low quality, fast measurement". The voxel size for this scan is 73 µm.
  - 5 scans with 5 parts per scan which is called "high quality, long measurement". The voxel size for each of the 5 scans is 47 µm which is lower than the previous one, thus it is referred as "high quality". On the other hand, 5 scans have to be performed, thus "long measurement".

CT Scan phase		Time [min]
Calibration		n/a
Scanning parameters		20
CT scan	1 scan with 25 parts	60
	5 scans with 5 parts per scan	300

Table 3: Time spent for each step of the CT scan phase.

4.3. Development of the measuring program and the measurement strategy phase

The time spent for developing the measuring program and the measurement strategy is illustrated in Table 4. Notes to be considered:

- The task "understanding of technical drawing" includes 2 telephone calls between DTI, Volume Graphics and Novo Nordisk to fully comprehend the alignment and the datum system.

- With the naming "Low automation", it is meant that only one measuring program was made, no matter if we have to analyse 1 scan with 25 parts or 1 scan with 5 parts. The scan data is manually imported, and the results are manually saved.
- With the naming "High automation", it is meant that one measuring program is made with the use of macros. Data evaluation (step 4) and execution of measurements (step 5) are fully automated, no manual tasks are required.

Development of Measuring Program and Measurement Strategy phase	Report [min]	
	Low automation	High automation
Understanding technical drawing	120	120
Preparing measuring program	100	1000

Table 4: Time spent for development of the measuring program and the measurement strategy phase.

4.4. Data evaluation phase

The time spent during the data evaluation phase is summarized in Table 5. Notes to be considered:

- The "surface determination" step is included in the "reconstruction of projection" task.
- "Low automation" includes a manual part identification. "High automation" includes an automatic part identification by the measuring program.
- The "part identification – high automation" task includes a template that creates region of interest in order to identify each single part in the scan. Once the part is identified, the point cloud of the single part is extracted and saved in a new file having the name of the part.

Data evaluation phase	Report [min]	
	Low automation	High automation
Reconstruction of projection	1	1
Surface determination	n/a	n/a
Part identification	10	1

Table 5: Time spent for the data evaluation phase.

4.5. Execution of measurements

The time spent during the “execution of measurements” phase includes measuring and reporting, and it is summarized in Table 6.

Execution of measurements phase	Report [min]	
	Low automation	High automation
Measuring & Reporting	70	28

Table 6: Time spent for the execution of measurements phase.

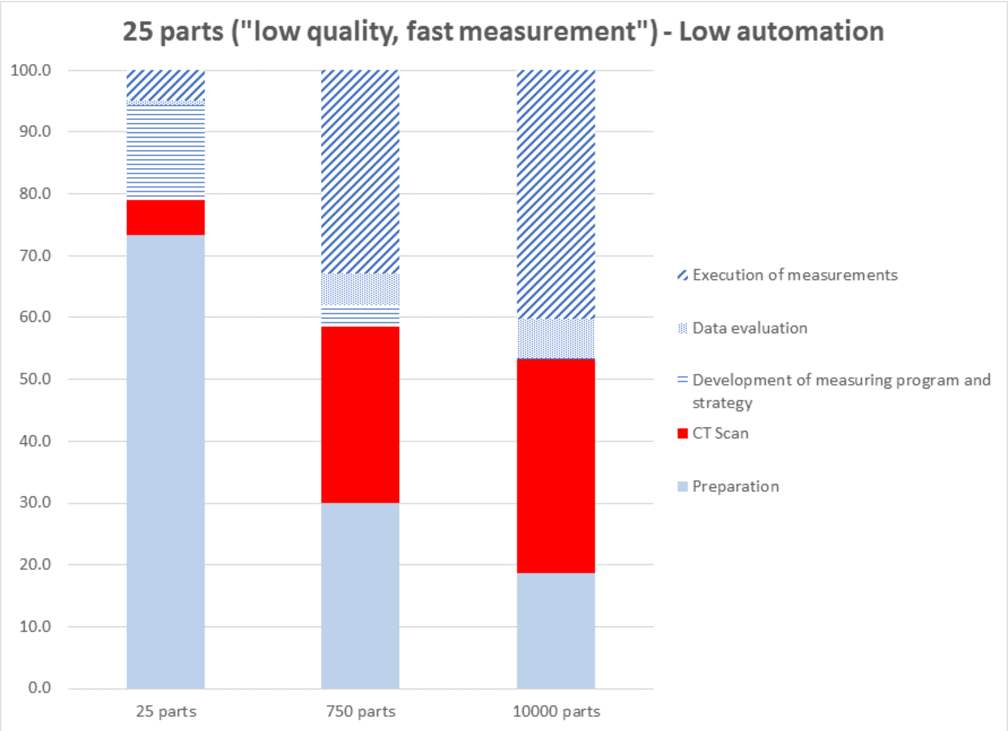
4.6. Sum-up

The results were analysed for 2 experimental investigations – 1 scan with 25 parts and 5 scans with 5 parts per scan – which were respectively called “low resolution, fast measurement” and “high resolution, long measurement” according to a “low automation” and an “high automation” measuring program. Afterwards these results were broadened up to scenarios of 750 parts and 10 000 parts by simply widening the duration of the tasks dependent on the number of parts to scan. These tasks were:

- Sorting of the elements
- Filling-up of the fixture
- Performing the CT scan
- Reconstruction of the scan projection
- Surface determination
- Part identification
- Measurement analysis

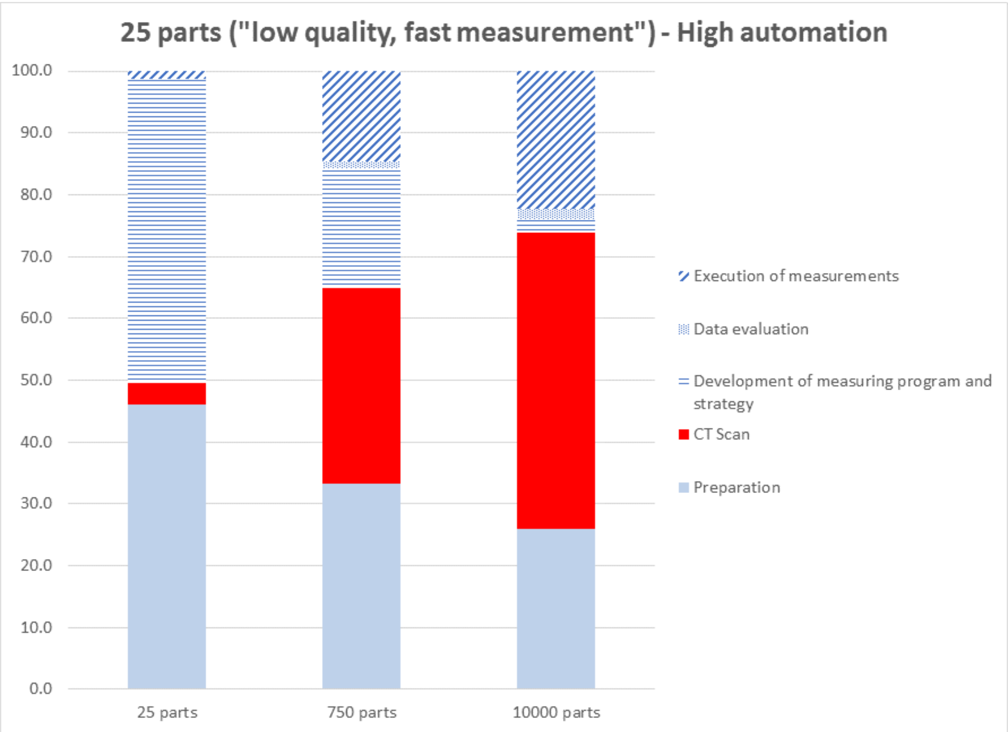
Results for 1 scan with 25 parts – low automation are illustrated in Figure 4, while results for 1 scan with 25 part – high automation are shown in Figure 5.
Figure 6 represents the results coming from 1 scan with 5 parts – low automation, while Figure 7 represents the results of 1 scan with 5 parts – high automation.

An important note is that the collected values do not differentiate between the time an operator is needed for manual steps and the time for the software to work on its own, which is cheaper.



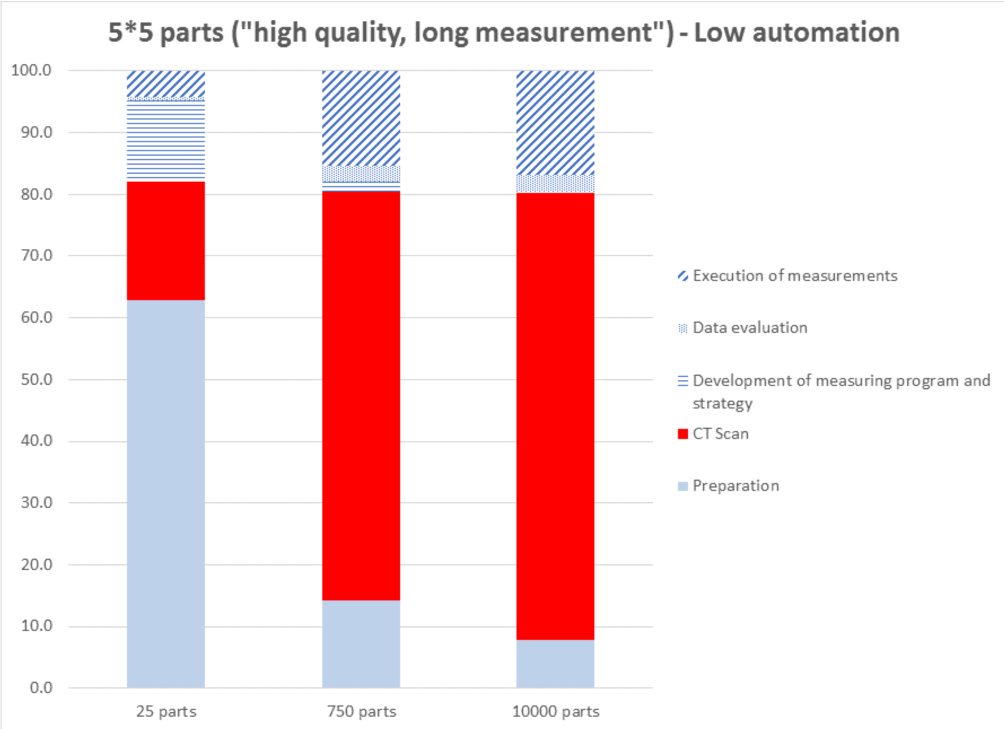
57.2 min/part 8.5 min/part 7.0 min/part

Figure 4: Results when 1 scan with 25 parts is analysed through a low automation measuring program.



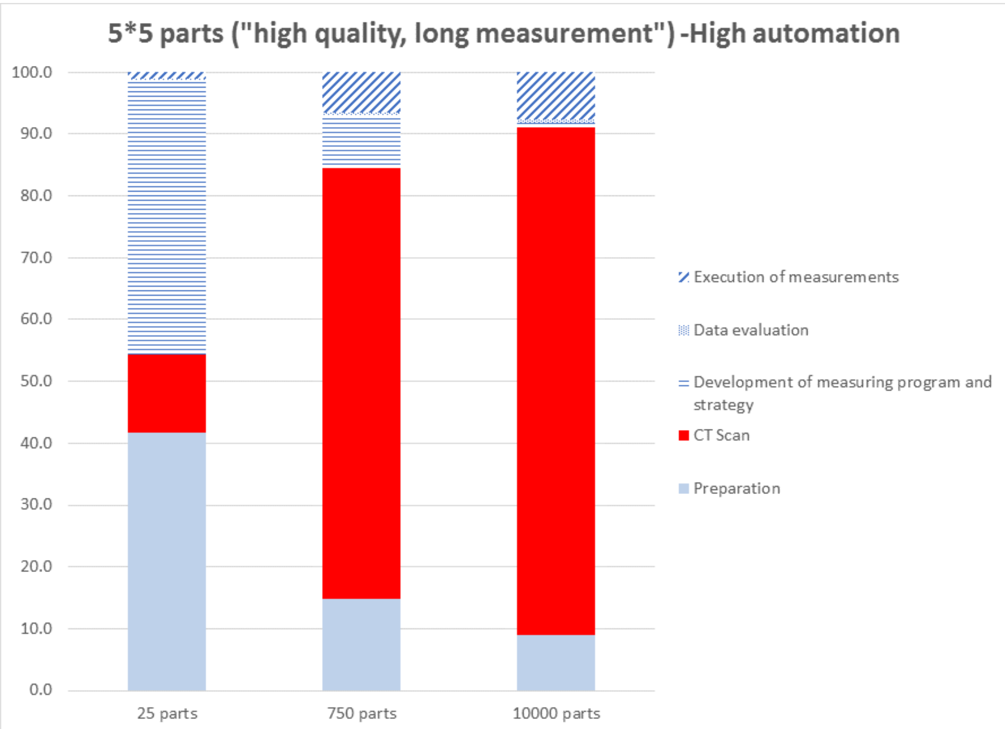
91.2 min/part 7.7 min/part 5.0 min/part

Figure 5: Results when 1 scan with 25 parts is analysed through a high automation measuring program.



66.8 min/part 18.1 min/part 16.6 min/part

Figure 6: Results when 1 scan with 5 parts is analysed through a low automation measuring program.



100.8 min/part 17.3 min/part 14.6 min/part

Figure 7: Results when 1 scan with 5 parts is analysed through a high automation measuring program.

5. Conclusion

Several conclusions and observations can be drawn from the graphs shown in chapter 4.

Low quality scan vs high quality scan:

- Low quality scan means that the voxel size is quite large and therefore there is the need to carefully select the larger possible voxel size to not compromise the final quality of the scan. It is important to identify the smallest feature to measure and be sure that this feature can be represented in the scan.
- On the other hand, low quality means a large volume to scan which leads to have more parts on the same scan, saving scanning time. This observation is shown by comparing the red column (CT scan phase) in Figure 4 and Figure 5 versus the red column in Figure 6 and Figure 7 and by comparing the overall measurement time per single part.
- High quality scan means that the voxel size is quite small, thus all the single features can be nicely detected in the part. On the other hand, a high quality scan leads to quite long scanning time and is not always the optimal setting in an industrial environment when results have to be handed over rapidly.
- In general, the specific part and features to be measured (including the associated tolerances) must be considered to identify suitable acquisition parameters while minimizing the scanning time.

Low automation vs high automation:

- Low automation means that most of the measuring tasks are performed manually. It is clearly visible that the time spent on developing the measuring strategy is quite insignificant in all the low automation cases. However, the data evaluation and the measurement execution growth with the number of parts reaching almost 50% of the entire CT pipeline, see Figure 4.
- High automation means perform all the scan analysis automatically. The development of such a measuring program is quite remarkable when dealing with a limited number of parts, see Figure 5. On the other hand, it allows a relative fast results evaluation (only 10% of the entire CT pipeline), see Figure 7.
- For smaller batches of parts to be measured (e.g. 25), low automation with manual steps seems faster, as no automated data evaluation must be set up. However, for larger batch sizes, the time spent - to create a fully automated data evaluation - is compensated, as time is saved for each measured part.

How much time does it take to scan this specific part?

- This is the most common question, while it does not cover all the critical tasks in a CT-pipeline.
- If the task is to measure 10 000 parts, then yes, the CT scan is the task that fill up to 80% of the entire CT-pipeline.
- If the task is to measure 25 parts in one scan, then the critical steps are the preparation phase and the development of the measuring program – especially when the part is new, the fixture needs to be designed from scratch and the technical drawing needs to be correctly understood before moving to the developing of the measuring strategy.

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