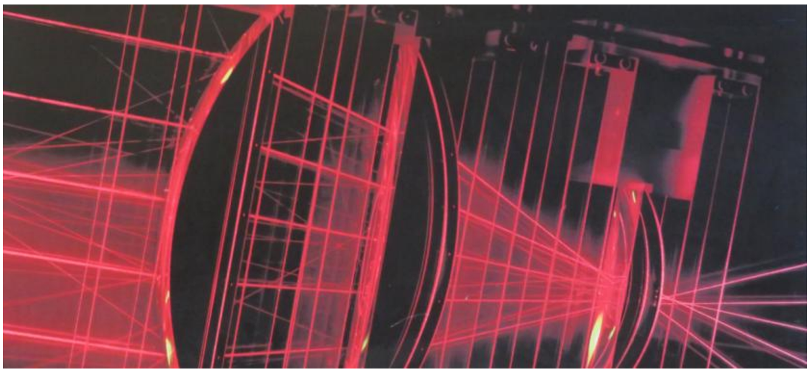
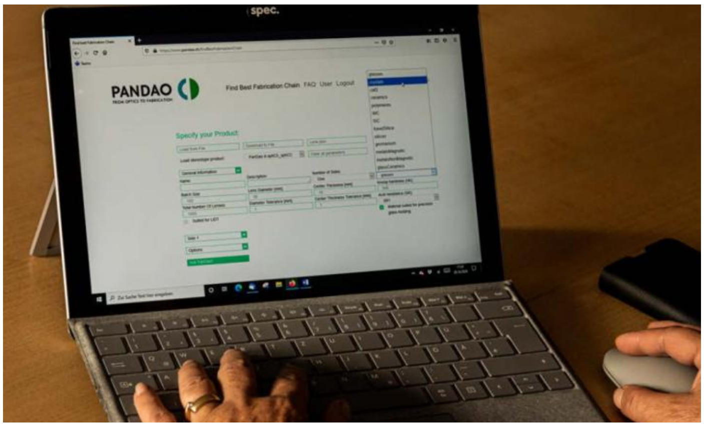
Manual

Frequently Asked Questions (FAQ)



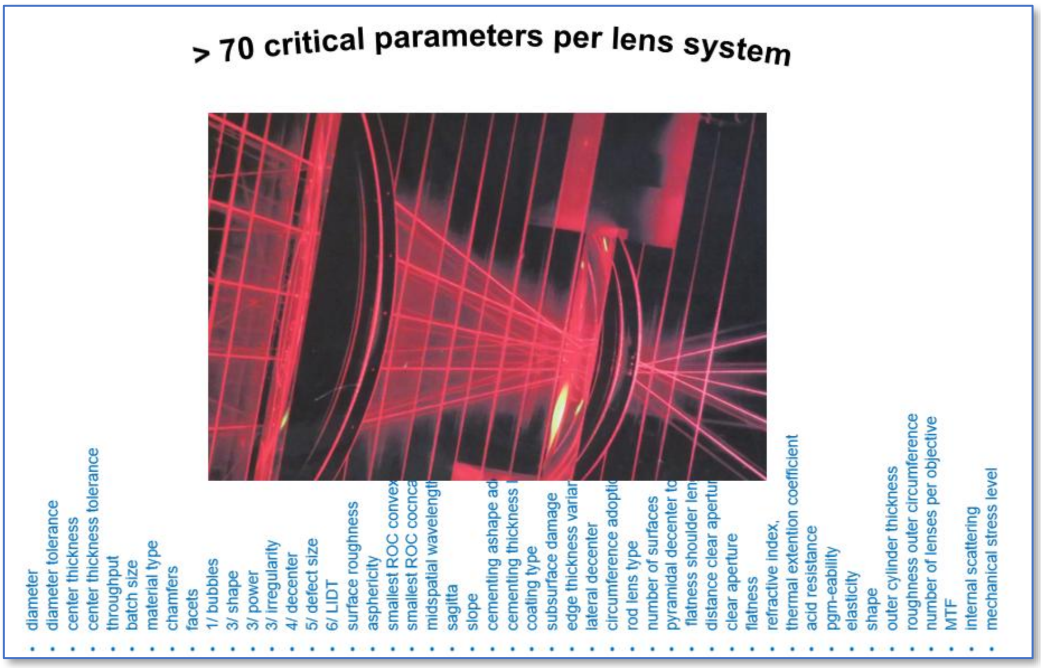
Content

1. GENERAL USAGE



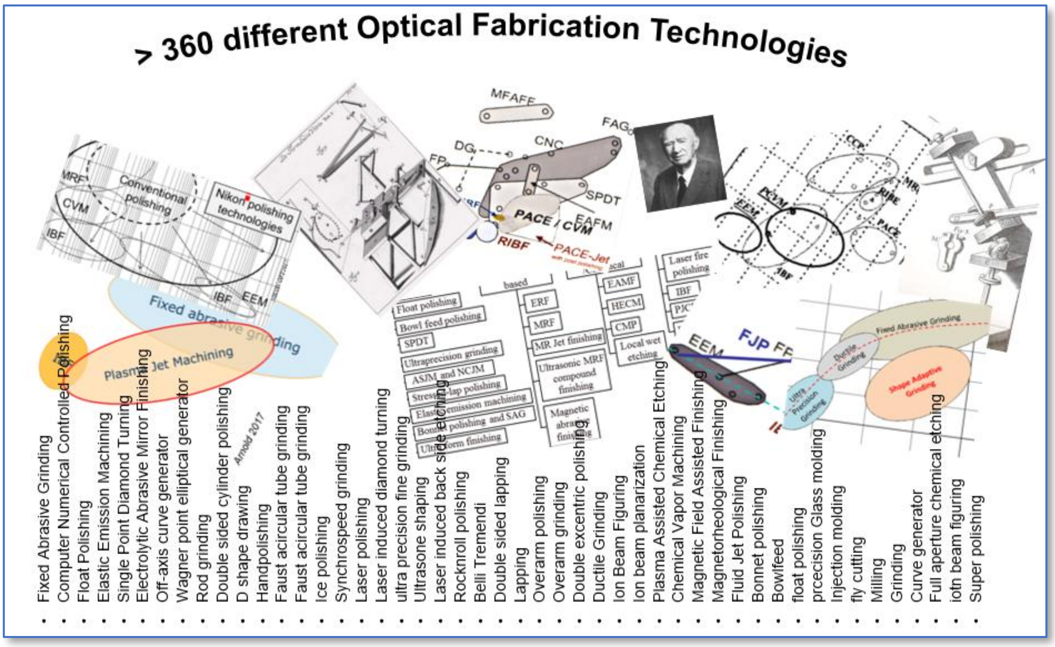
Lens to Optical Fabrication Technologies to PanDao to SMART OPTICS FACTORY

Optical products are defined as elements and systems that allow light to travel through. Consequently and dramatically, optical products cover a huge range of applications from XR projectors to defence systems to medical implants and endoscopes to telescopes and satellite systems to LIDAR for self drining cars to illumination systems, etc.



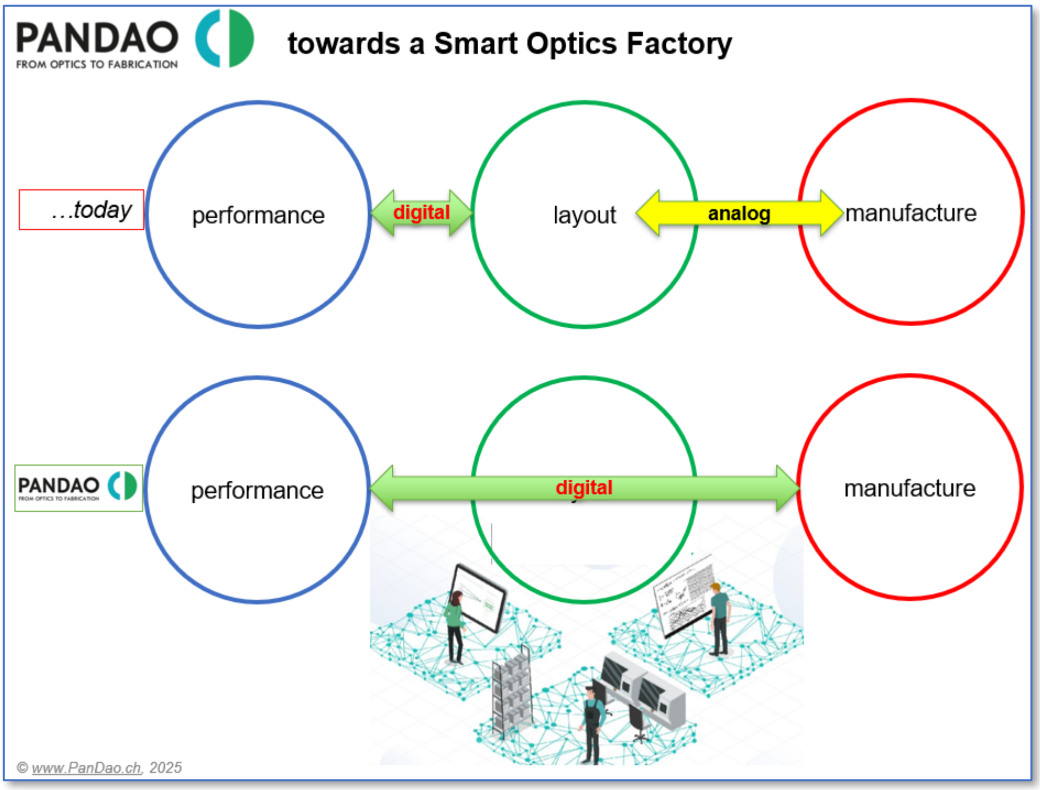
It takes more than 70 parameters and tolerances to sufficiently describe an optical element, e.g. a lens, mirror or prism.

There are about 360 Optical Fabrication Technology Techniques (OFTTs) for the generation of optical elements whith diameters ranging from 0.2 mm (endoscopy) to 9.4 m (telescopes) and materials ranging from organic glasses through mineral glasses, crystals up to hard metals (e.g.WC) and nanomeres.



There are about 360 different optical fabrication techniques (OFT) to be employed in fabrication chains to generate optical systems as a product

PanDao marks a significant step towards a Smart Optics Company. By closing the analog gap between optical design and optics manufacturing, PanDao enables digital communication along the whole development chain of optics products mastering: from optical design to fabrication to sales to supply chain.

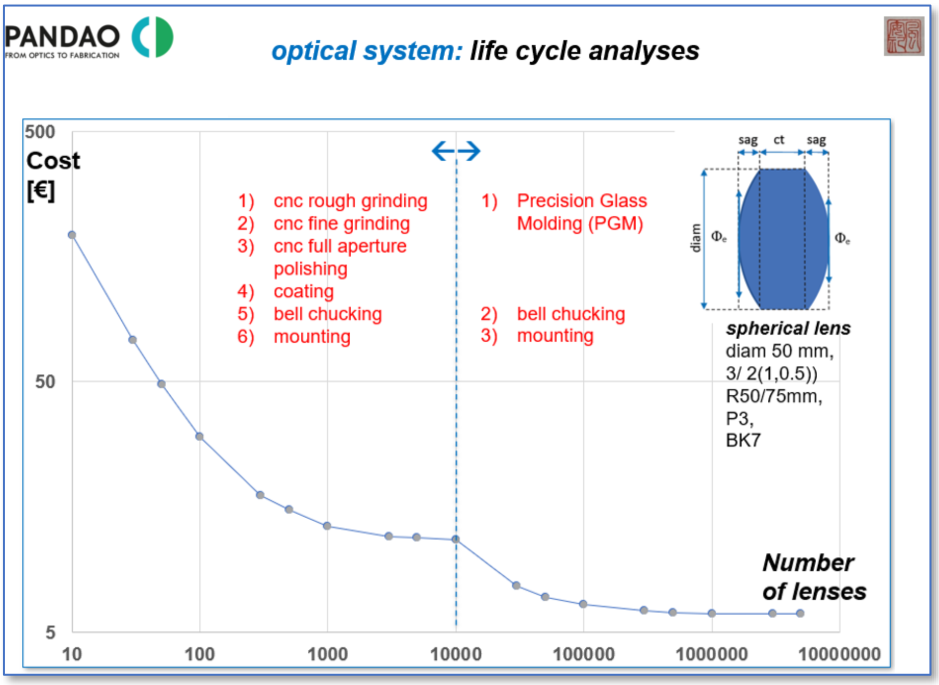


PanDao digitalises the last analog gap along the generation workflow of an optical product.

PanDao is the first solution that managed to digitalise all 360 OFTTs in such a way, that they can communicate with key parameters of optical porducts. This enables for the first time ever the simulation of whole fabrication chains, determining the optimum fabrication chain for a given lens at minimum cost and risk.

PanDao reads in lens data (according to ISO10110 or MIL standard) and determines the optimal fabrication chain at minimum cost and risk.

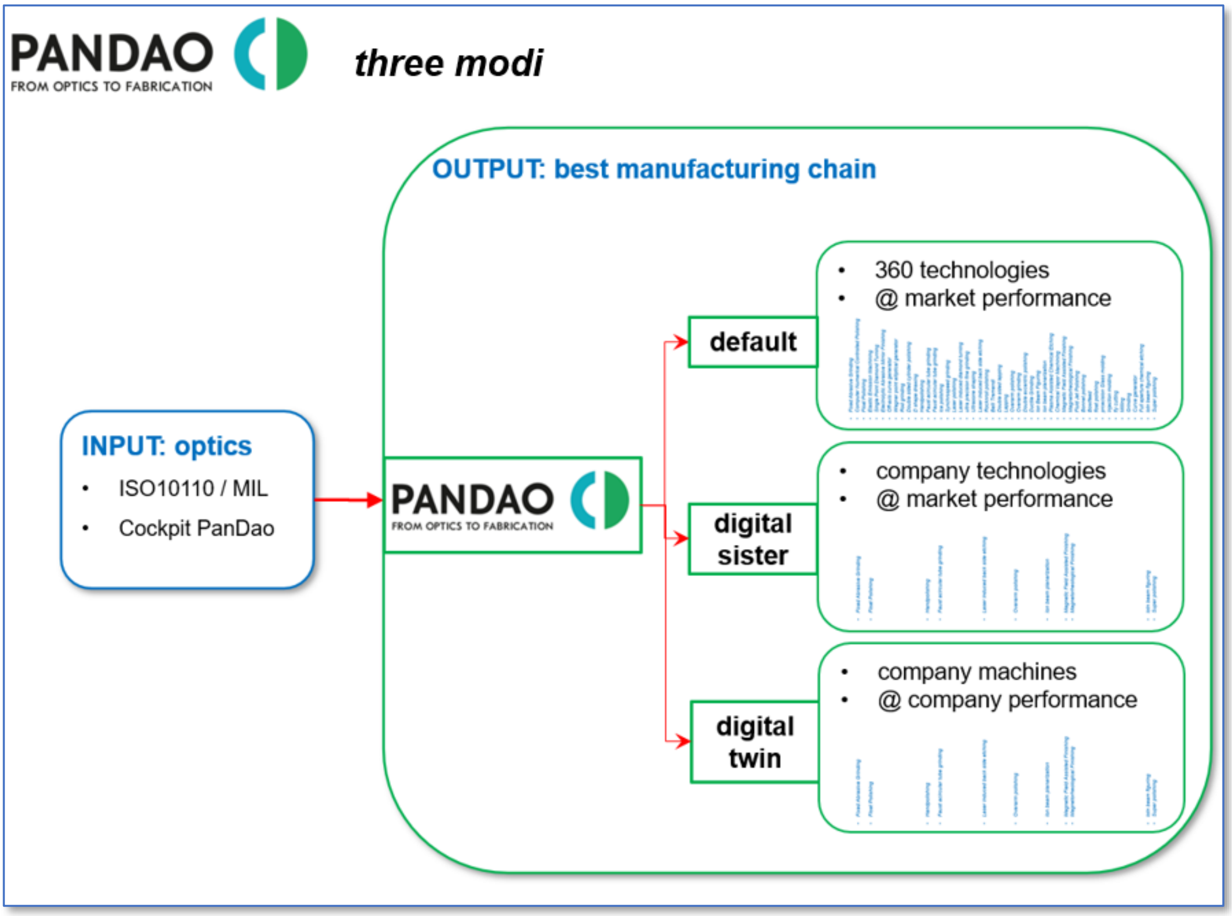
- PanDao enables ***optics designers*** to optimize their designs for minimum fabrication cost and thus saving substantially:
  - It takes usually a maximum of 6 to 8 "ask PanDao" requests to optimize a two-sided lens, which can save up to thousands of Euros (taking into account a typical European batch sized fabrication order of some hundred lenses, only).
- PanDao informs ***purchasing managers*** and ***optics engineers*** about producibility of optical designs:
  - It takes only one "ask PanDao" request to receive information about (a) the best fabrication chain, (b) essential technologies needed and (c) fabrication cost level.
  - Having that data, you are able to choose the optimum supplier at minimum risk and to negotiate the best price, usually with a considerable savings potential.
- PanDao informs ***executive management*** and ***controlling*** about fabrication cost performance of their in house production department with respect to State-of-the-Art in industry.
- PanDao supports ***optical shop floor managers*** and ***production planners*** in optimizing their fabrication chains, steering the capacity of in-house technologies, and evaluating investment projects for new technologies to be implemented.
- PanDao enables **supply chain managers** to reach fair deals with suppliers and to plan optimum supply chains along the life cycle of an optics product from prototyping through serial production towards out-phasing at the end.



PanDao life cycle analysis of a lens' supply chain from prototyping to serial production.

PanDao can be used with three different databases:

- PanDao default database,
- PanDao digital sister (the company-owned database),
- PanDao digital twin;



PanDao can handle three different data coulds: default, digital sister and the digital twin.

Three PanDao modi			Commercial boundary conditions		
			default	**applied for: bank loan, uptimes and salaries**	**of your workshop**
default	**360 technologies @ market performance** This is PanDao's standard setup. It provides access to over 360 technologies and shows how they perform in the market. This enables you to explore and benchmark market-level data.	Default Included in the single-user and/or company-wide licence usage.	ok	ok	n.a.
digital sister	**company technologies @ market performance** This option provides an additional, separate access point to PanDao, limited only to the technologies currently used within your company. It provides a focused view of your internal technology landscape while maintaining full market access via the default setup.	Add-on to default Fixed price for setting up one workshop. → Includes setting-up data and installation of digital sister for one workshops technologies.Subsequent database mutations upon request and quotation.	ok	ok	n.a.
digital twin	**company machines @ company performance** In this advanced setup, which provides a third separate access to PanDao, we securely read and integrate data from all your machines under an NDA. This creates a full digital replica of your machinery and their performance. This allows you to directly benchmark your machines' performance against the broader market.	Add-on to digital sister Price for setting up one workshop upon request and quotation → Includes setting-up data and installation of digital twin for one workshops machinery. Subsequent database mutations upon request a.nd quotation	n.a.	n.a.	ok

(1) Single-user license
- personalized single user
- non-transferable
- unlimited number of PanDao requests.

(2) Company-wide license
- not personalised
- multiple users, can be used company wide
- e.g. 200 requests serve 50 cases

(3) Engineering services
- NDA protected
- PanDao does all the work for you

And there are three ways to get access to PanDao's services:

- single-user license,
- company-wide license,
- Engineering (DesToFab) service.

For further informations, please consult the our references at the end of this document and contact us at *info@PanDao.ch*.

- **Invited paper** Spectaris GmbH and Fraunhofer ILT, "KI in der Photonik, Leserfertigungstechnik und Optikdesign», Berlin, Germany, 2025
- **Invited paper** O.Faehnle, "The smart optics factory", Optica's Optical Design and Fabrication congress (ODF), Denver, USA, June 2025
- T.Pickering, E.Elliott, E.Lepekhin, N.Papachristou, P.Chiu, O.Fähnle, M.Tinner, E.Langenbach, "Translating Optical Design Specifications into Manufacturing Terminology: Bridging the Gap Between Designers and Manufacturers", SPIE conference on "Precision Optics Manufacturing", Deggendorf Institute of Technology, Deggendorf, Germany, May 2025
- **Journal paper:** Oliver Faehnle, "Process optimization in optical fabrication", SPIE Journal on Optical Engineering 0001;55(3):035106. doi:10.1117/1.OE.55.3.035106., 2016

What is the best way to learn how to use PanDao and to stay up-to-date?

Each purchase of a PanDao license includes a free beginners training of about 1.5 hours; additional training sessions are available. In addition, the PanDao team gives regularly advanced training courses (e.g. at conferences or exhibitions) and webinars.
For further informations, please contact us at info@PanDao.ch.

Which topics are covered by PanDao?

For a complete list of topics covered by PanDao, please refer to the ***development stage*** listed in chapter 5 of this manual.

Which topics will be added next to PanDao?

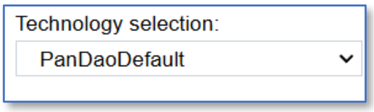
The next topics to be added are determined by PanDao customer surveys and are displayed in Chapter 5, the development stage.

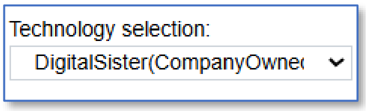
How does PanDao work?

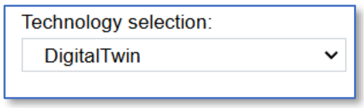
PanDao reads in optics elements data (according to ISO10110 standard) and determines the optimum supply **chain**. To that aim, different sets of technologies are competing with each other:

- Read-in your optical elements with one click from optical design software tools: CodeV, Zemax and Quadoa;
- fabrication cost: **360 optical fabrication technologies (OFT) are competing** to generate the **optimum optics fabrication chain** for a given optical element: The most-cost efficient chain and the fastest chain;
- center grinding cost: **6 center grinding technologies are competing** to be applied as the most cost-efficient technology for a given optical element: either a single element or a cemented lens group;
- cementing cost: **8 cementing processes handled by humans or robots are competing** to cement optical elements goups (e.g. doublet);
- splitting cost: **9 splitting processes are competing** to separate optical elements out of e.g. a waver or a prism strip.

PanDao can be operated using three different databases which can be selected in the *cockpit* section of the input data surface. Please note that option “b” (digital sister) and option “c” (digital twin) are upon special request only and are not included into the PanDao default package:







a) ***Default***: optimal fabrication chain is determined out of about 360 different optical fabrication technologie techniques (OFTTs) performing at State-of-The-Art processing level.
b) ***Digital sister (Company-owned)***: is an extra option where the OFTTs of your company are used (protected by NDA). That way, PanDao can generate the optimal fabrication chain using only OFTTs available at your company. Digital sister technologies are considered performing at State-of-The-Art level.
c) ***Digital-twin***: is extra option where the OFTTs of your company are used (protected by NDA) together with their individual machining performances in your workshop. That way, PanDao can generate the optimal fabrication chain using your companys customized OFTTs performing at your individual machines level of quality, throughput and cost structures.

What is PanDao’s policy in handling my optics data?

As a principle (see GTC) PanDao tries to store as less user data as possible. If not explicitly allowed in the user tab, any optics data entered into PanDao is only used to calculate the result and immediately after that lost on the server side. Your optics data is not stored on the server and can therefore not be stolen if there would be a security breach on our side. The transfer of the data to the server is protected by https encryption. If you use company-owned or digital twin OFTTs than your data will be hard compiled into PanDao will therefore be really hard to extract if there would be security issues.
The only data stored on our side are the user data entered at registration. On the client side (the device using PanDao) the last optic requested and the last result displayed are stored in the local cookies. We can not influence how you handle security on your devices. If this is a concern for you please discuss this with your companies IT department.

Therefore, using PanDao is substantially less IP risk than spreading technical drawings to suppliers for receiving a quote or having the optics being prodiced. At suppliers and workshops, your technical drawing and all critical data is usually printed out and spread through-out the company, including production departments where your technical drawings often are even attached to the machines and visible.

How is the cost calculation in PanDao composed?

PanDao's cost calculations

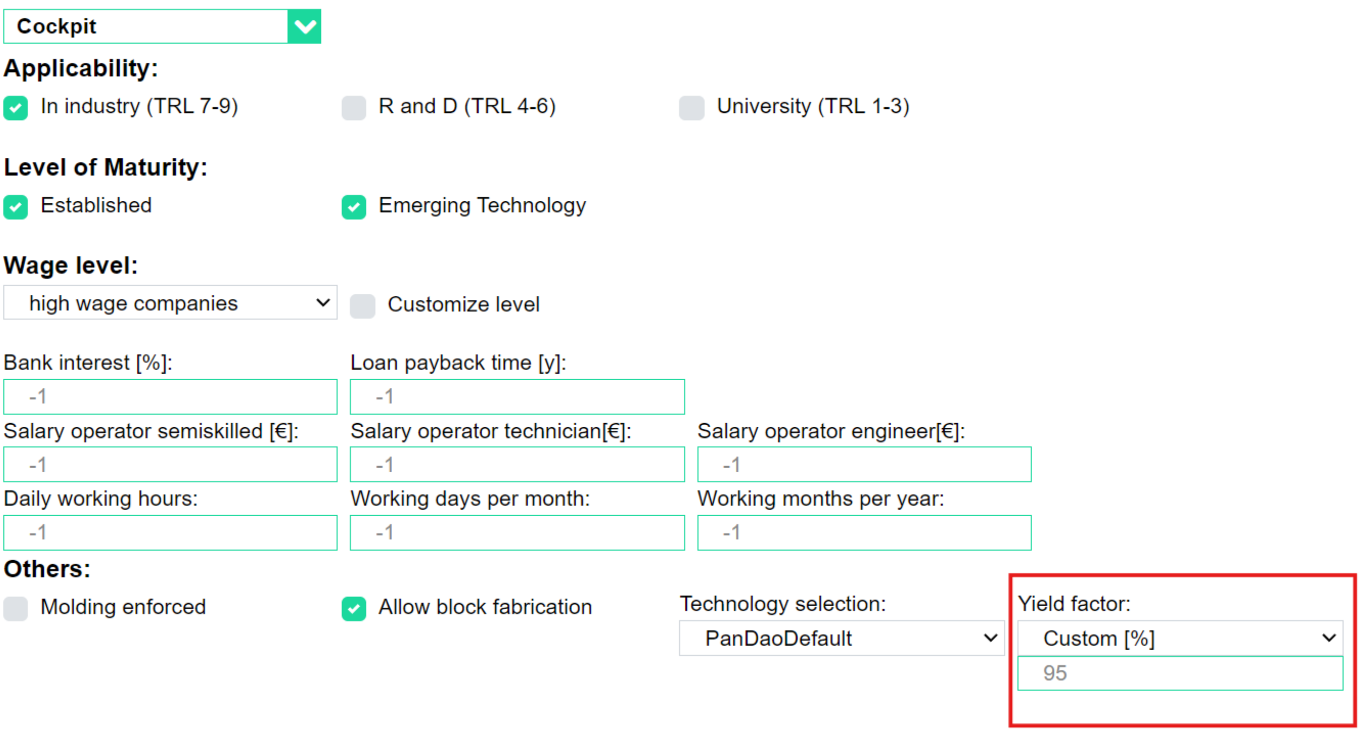
a) ***including***: machining, tooling, operators' salaries and attention needed, setup machine, machine's invest cost, bank payback time and interest, workpiece material, center grinding, protective chamfering and facets, non-circular circumference generation, workpiece mounting, dismounting, quality testing during fabrication, coating, uptime and downtime of machines per day, month and year, etc.;
   - Please note that when determining the machining cost, PanDaoi always assumes that the machine has not yet been depreciated (this means that when the depreciation period of a machine is reached, a new machine is purchased again to keep the machinery up to date).

b) ***excluding***: companies' overhead, assembly, packaging and delivery cost.

Which yield level is considered by PanDao?

By default, PanDao applies optics manufacturing at a high industrial quality level, aiming for a yield of 95%. To achieve this goal, an overproduction of 5% is considered. Thus, if 100 lenses are to be produced, PanDao assumes a production quantity of about 105 lenses.

In the cockpit tap a custom yield factor can be specified:



How does PanDao manage to stay up to date?

In order to ensure PanDao's State of the Art level, PanDao is regularly being updated: for more details, please consult the blog section at the PanDao webpage (www.PanDao.ch) and PanDao's LinkedIn page (www.linkedin.com/company/pandao-gmbh) or contact us at info@PanDao.ch.

How do I get started?

Each purchase of a PanDao license includes free training sessions; please contact us at info@PanDao.ch.

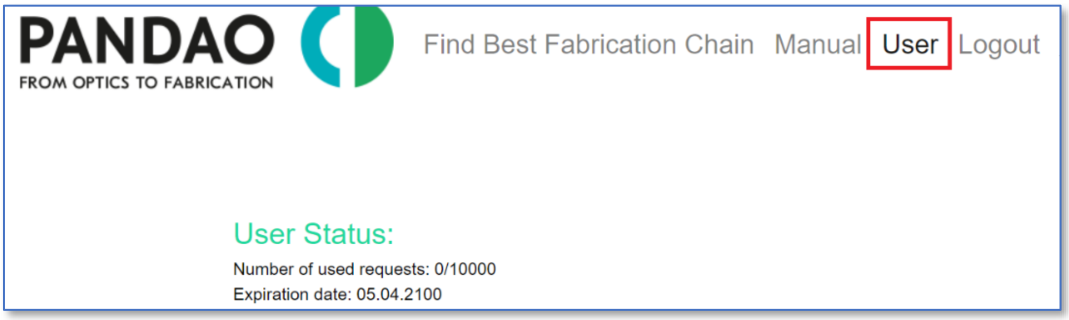
The best way to get started is:

- follow the free PanDao training sessions that are included in any license purchase,
- consult this manual,
- check out the videos on our YouTube channel,
- read our publications (see reference list at the end of this document),
- follow us for frequent news and tips and tricks at PanDao's LinkedIn page,
- read our blog entries at www.PanDao.ch and
- consider to book extra training sessions with PanDao's team, if needed,

To start PanDao, please log in at www.PanDao.ch using the log in data you received with your license.

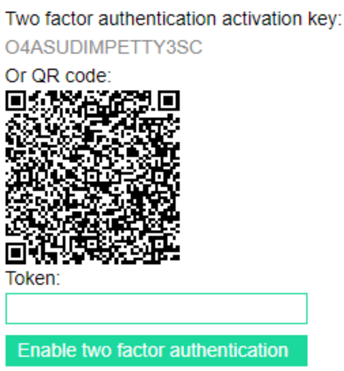
Where can I check my current number of PanDao requests?

Please check the "PanDao/user" site which is located here:



How do I activate two level authentication?

Please navigate to the PanDao/User site and scroll down. There is a section where a QR code is displayed:



You then need to scan the QR code or manually enter the activation key in your favorite two factor authentication app or plugin. For testing we used the [chrome authenticator plugin]() and the [google authenticator app](). Then enter the generated token in the "Token" field and press "Enable two factor authentication". A success message should appear. If two factor authentication is enabled every time you log into PanDao you have to enter an additional token which is generated by the plugin or app you have chosen. You can also disable this option on the users side. If you somehow are not able to generate tokens anymore (For example because you deinstalled the app you used) please contact info@pandao.ch to reset the option.

Is PanDao generating fabrication cost or selling price?

PanDao generates fabrication cost, without any financial security cushion along the fabrication chain.

How does PanDao deal with the wage levels of different countries and companies?

Please note that in every country the wage level of different companies might differ and that production qualities not necessarily depend upon the wage levels. PanDao distinguishes 3 different types of companies; high wage companies, medium-wage companies and low-wage companies. In addition, it is possible to enter one's own commercial conditions into PanDao.

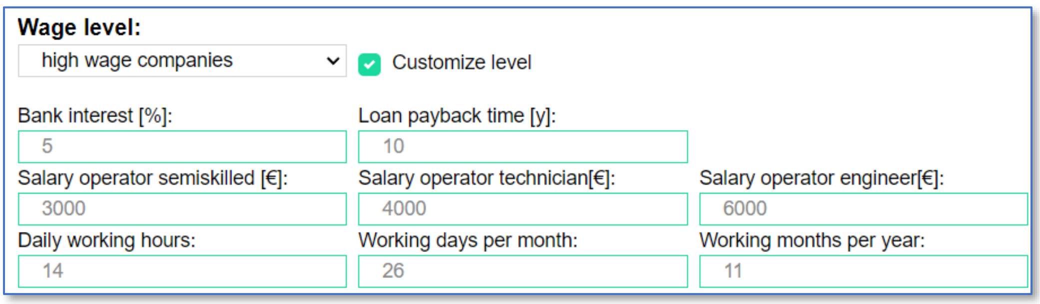
The wage level can be adjusted in the cockpit section.

Why is there a difference between absolute fabrication cost between my company's production department and PanDao?

Please consider that PanDao is determining fabrication cost and not selling price. PanDao is not dealing with companies' overhead cost, assembly, packaging and delivery cost.

In order to be able to compare absolute cost levels, ensure that you are comparing the same fabrication chain.

Please customize the wage level of your or your supplier's company in the cockpit section:



The delta that might remain depends on the following information that would be requested by PanDao:

- all individual commercial information of your company, e.g., varying bank interest rates and level of salaries, invested machines cost and age of machines applied etc.,
- detailed description of the fabrication chain currently in use (types of machines, tools and processes etc.) and which machines are currently depreciated,
- calculating machining cost, PanDao takes only machineries into account that are applied along the fabrication chain; often departments hourly rates are calculated based on all machinery existing within the department including those, being not used this time,
- calculating operator cost, PanDao takes operator hours needed for this lens into account and not salaries of all people being employed within this department.

Additional notes:

- The calculation still depends on the basic wage level chosen. Just the customized parameters are overruled. For example, the tooling cost is still depending on the base wage level set. Otherwise, the user has to input tooling cost for all 350 technologies which is not feasible.
- The salaries are monthly values
- If your machines are already amortized, please choose a low bank interest (for example 0.0001) and a long loan payback time (1000 years) to account for this.

2. INPUT PARAMETERS

2.1. ALL SHAPES

How should I describe my lens parameters and tolerances

PanDao reads in optics elements data according to ISO10110 standard and determines the optimum fabrication chain.

Flats to Freeforms: The Optical Engineer’s Stairway of Complexity

This chapter analyzes the Stairways from Flats to Freeforms from the point of view of manufacturability, identifying at each level the dominant parameters that define what can be reliably produced in optical fabrication. It links symmetry, process control, and metrology into a structured “stairway of complexity” that guides practical engineering decisions.

Introduction

In optics system generation, communication often feels like a “Chinese whispers game”. From system users (e.g. astronomers, doctors or AI driven LIDAR systems) to optical designers, to fabrication engineers to workshop technicians, information passes through many hands: Each fluent in a different language. Precision can get lost in translation.

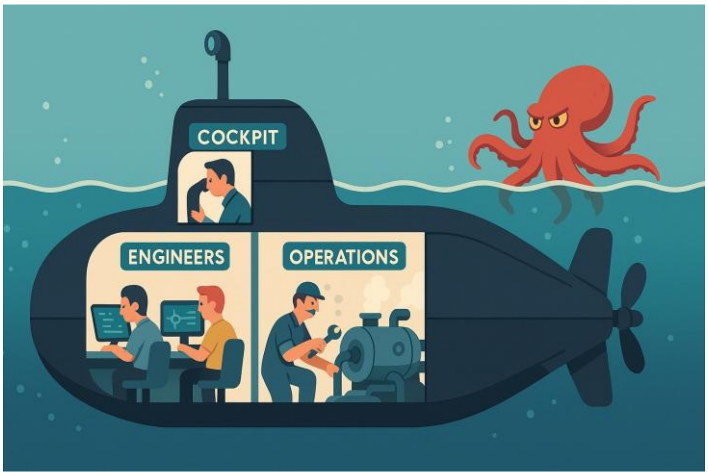
Today’s optical systems are generated in a three step process:

1. Design and systems layout out carried out by optical designers applying optical design software tools (like Quadoa, Zemax, CodeV, Oslo, etc.). During this first process step, the application parameters (like MTF, image resolution, dB) are translated into the optical systems parameters (like refractive optics, number of optical elements, types of glass lenses applied: their shapes, dimensions, geometries and qualities).

2. Subsequently, the design and layout of the optimum fabrication chain for the designed optical system has to be determined. This is typically done by senior optical fabrication engineers applying their know how and experiences – and more recently this process step has been digitalised by PanDao [1], a software tool that interprets optical designs and models the optimum fabrication chain required.

3. Finally, the optimum fabrication chain is being set-up either at your or at your chosen suppliers workshop and production is started.

This paper focusues on different types of lenses, flats, sphericals, asphericals and freeforms, analysing their key characteristic parameters – not from an optical design point of view – but from a manufacturability point of view: the PanDao language of manufacturability applied to one of the optical designers parameters: The lens’ shape.



PanDao helps you to navigate your way from the flat ocean surface to the freeform shapes of the abyss.

We travel in a submarine full of optical system engineers, diving from the calm surface of flat optics to the deep, shifting geometries of freeforms. Each step demands mastery of one dominant parameter:

Lens shape: a stairway of complexity			
Surface Type	**Dominant matters to master**	**Dominant Parameter**	**Order**
Flat	f(x)	Shape	0th
Spherical	f'(x)	Slope / Inclination	1st
Aspherical	f''(x)	Curvature (ROC spectrum)	2nd
Freeform	f'''(x)	Change of Curvature (ROC variation)	3rd

Flats — Mastering Shape f(x)

Definition
A flat surface features planar symmetry and represents the zero-order case:

z = f(x, y) = const.

Its radius of curvature is effectively infinite (on Earth, a perfectly flat surface would match R ≈ 6,400 km).

Manufacturing focus
Generation of a flat, transformationally symmetric surface with focus on its planarity shape function f(x). The smallest stress, imbalance, or edge deviation shows up immediately. Main controls are flatness and wedge.

Metrology
Various types of interferometers, Fizeau with transmission flats; three-flat method; autocollimation; WLI/AFM for roughness.

Manufacturing flats risks
Turned edge, wedge error, mount print-through (quilting), mounting or thermal distortion.

Sphericals — Mastering Slope f'(x)

Definition
A spherical surface features point symmetry around a defined optical axis and a constant radius of curvature. Sag for radius r:

z(r) = R - sqrt(R^2 - r^2) ≈ r^2/(2R) + r^4/(8R^3) + …

Manufacturing sphericals focus
The key challenge is inclination (the first derivative f'(x)), which increases steadily toward the rim and reaches its maximum as the surface approaches a hemisphere (diameter = 2R). Maintaining stable removal conditions and precise axis definition are critical for preserving form accuracy.

Metrology
Interferometry with transmission spheres; cat's-eye/ROC checks; spherometer/profilometer.

Manufacturing risks
Zonal rings, local peak or dip in the center, mis-centration/tilt, turned edge, mistakenly swapped test plates (wron radius).

Asphericals — Mastering Curvature f''(x)

Definition
An aspherical surface features rotational symmetry around its optical axis. Compared to the simple steepness of sphericals, asphericals introduce controlled deviations from the sphere to correct optical aberrations and expand design freedom. Conic with higher-order terms:

z(r) = r^2 / [R (1 + sqrt(1 - (1 + k) (r^2 / R^2)))] + A4 r^4 + A6
r^6 + A8 r^8 + …

Please note, that is it also possible to describe aspherical shapes using Zernike polinomials [2].

Manufacturing asphericals focus
The dominant challenge is curvature (the second derivative f''(x)). Material removal must follow the local curvature distribution with high precision, managing both curvature gradients and slope variations. Deterministic sub-aperture processes such as CNC polishing, MRF, and IBF are typically used, each of them generating typical mid-spatial structures themselves.

Metrology
Null interferometry (CGH/null lens); profilometry; stitched interferometry; deflectometry.

Manufacturing risks
Zonal curvature deviations, slope-variation spikes, MSF ripple/stitch, and mis-registration between machine/test frames.

Freeforms — Mastering the Change of Curvature f'''(x)

Definition
A freeform surface has no symmetry; its general form is given by:

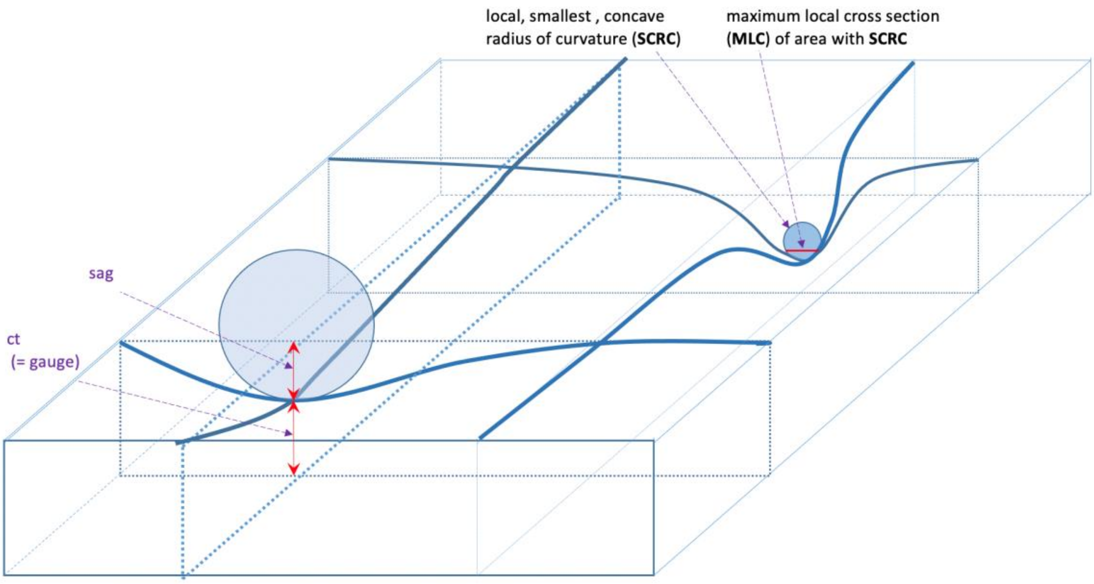
z = F(x, y)

As the freeform shape origins from optical raytracing during the optical design of the system, it is in the nature of the matter that freeforms often are described by Zernike polynomial coefficients [2].

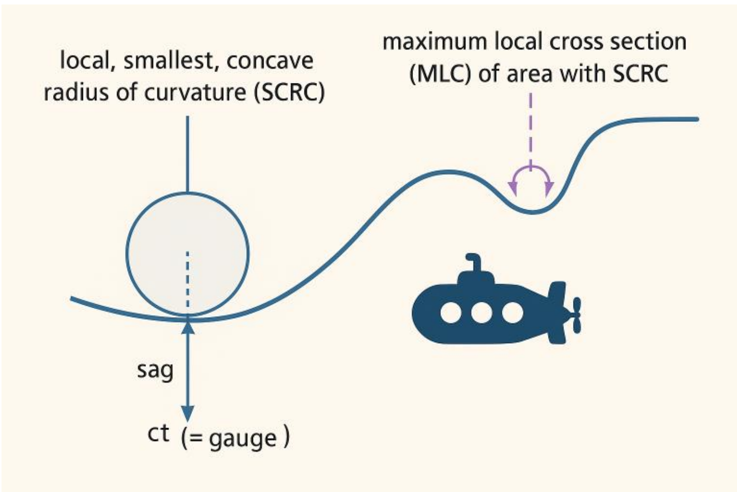
Manufacturing freeforms focus

Freeforms are characterized locally by two principal curvatures, k1 and k2, that vary independently across the surface. The dominant challenge is not the curvature spectrum itself, but the change and rate of change of curvature—the third derivative f'''(x)—creating a dynamic curvature landscape.

In the golden age of wooden sailing ships, master shipbuilders carried a magazine of wooden splines [3]: Local shape templates used to form the optimal hull curvature. These splines were the binary ancestors of freeforms, physical embodiments of f'''(x) long before the term existed. Today, digital optical tools play the same role, shaping surfaces with mathematical splines that adjust every few microns, where the shipbuilder's templates once changed only every few feet.



Freeform-parameter sketch: conceptual isometric sketch indicating SCRC, MLC, localSag, and gauge.



Freeform-parameter diagram showing cross-section with SCRC, MLC, localSag, gauge, and a tiny submarine below the glass surface.

Manufacturing freeforms focus
The producibility of freeforms depends on process stability and tool accessibility. The key manufacturing parameters used to determine the optimal production chains – as currently applied within PanDao [1] – are as follows:

- SCRC — Smallest Concave ROC: value [mm], location (x,y), direction.
- MLC — Max Local Cross-section at SCRC: width [mm] across the SCRC pocket; default 0.01 mm if curvature is continuous.

- localSag @ SCRC — Depth [mm] of SCRC pocket relative to tangent plane: localSag = R_SCRC − sqrt(R_SCRC^2 − (MLC/2)^2).
- Gauge — Minimum thickness [mm]; may occur away from SCRC.
- minROC / maxROC — [R1,min, R1,max, R2,min, R2,max] [mm]; note sign changes (saddle zones).
- Max relative change of ROC — max | (1/R_i) (dR_i/ds_i) | [% / mm].
- Max absolute change of ROC — max | R_i(s+Δs) − R_i(s) | for Δs = 0.01, 0.05, 0.10, 0.50, 1.00 mm, 2 mm and 5 mm.

Dominant factors to be mastered during freeform generation

Parameter	Meaning / Definition	Units	Default / Note
SCRC	Smallest Concave ROC; specify value, (x,y), and direction.	mm	Defines local tool limit (tightest concavity).
MLC	Max local cross-section at SCRC pocket.	mm	Use 0.01 mm if curvature is continuous.
localSag @ SCRC	Local pocket depth relative to tangent plane.	mm	R_SCRC - sqrt(R_SCRC^2 - (MLC/2)^2)
Gauge	Minimum material thickness (may be away from SCRC).	mm	Important for deformation and fixturing stability.
minROC / maxROC	Principal curvature bounds across the clear aperture.	mm	Report R1,min, R1,max, R2,min, R2,max; note sign changes.
Max relative change of ROC	Normalized rate: |(1/R_i)·(dR_i/ds_i)|.	% / mm	Drives dwell stability and null sensitivity.
Max absolute change of ROC	Absolute change over Δs = 0.01–1.00 mm, 2mm and 5mm.	mm	Tool-scale ROC change (10–1000 µm steps).

Metrology
Deflectometry, profilometry, 3D scan/CMM, data modal fits (Zernike/XY/B-splines).

Manufacturing risks
Mis-registration (mismatch of coordinate frames) between testing and manufacturing; unreachable concavities; false tool positioning due to tool mass acceleration effects; dwell instability in high f‴ regions; distinguish shape error vs sample tilt vs lateral mis-alignment.

Conclusion

By diving deep along this stairway from flats to freeforms, we identified the key manufacturability parameters that workshop engineers and PanDao depend-on to turn optical designs into reality.

Surface Type	Symmetry	Dominant Parameter	Manufacturing Focus	Typical Risks
Flat	Planar symmetry	Shape (f)	Planarity (flatness, wedge)	Turned edge, wedge, print-through
Spherical	Point symmetry	Slope (f')	Control of inclination near hemisphere	Zonal rings, center dip, tilt

Aspherical	Rotational symmetry	Curvature (f'')	Curvature & slope-variation control (CNC/ MRF/ IBF/ Bonnet)	Zonal spikes, MSF, mis-registration
Freeform	No symmetry	Change of curvature (f''')	Curvature-change rate, tool access, registration	Tool reach, dwell instability.

References

[1] www.Pandao.ch
[2] https://pandao.ch/zernike-form-to-asphere/
[3] Nowacki, Horst, and Matteo Valleriani (eds.), Shipbuilding Practice and Ship Design Methods from the Renaissance to the 18th Century: A Workshop Report, Max Planck Institute for the History of Science, Preprint 245, 2003.

PRO-OPTIC-CONVERTER: How can I determine and convert lens tolerances so that PanDao can read them in?

You can export lens data from your optical design software tool in a format that PanDao can read in.

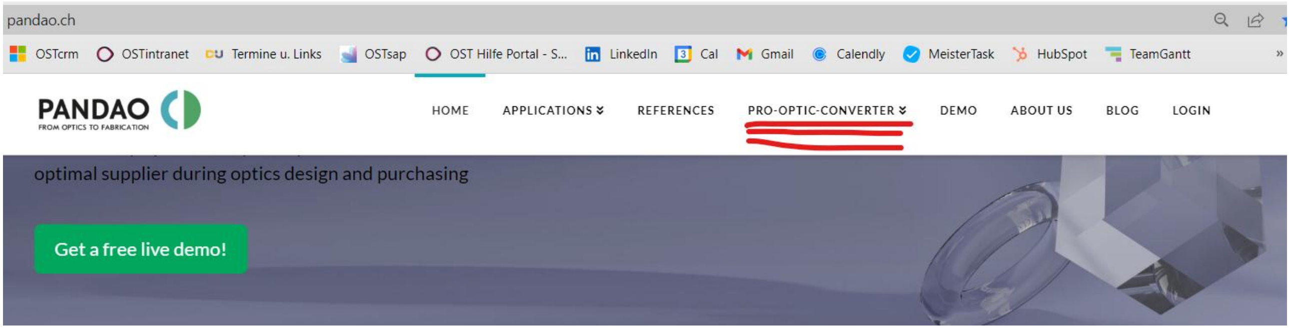
Nevertheless, often technical drawings use different ways to describe tolerances (like the radial tolerance in mm instead of the power value in fringes) or apply different standards (such as the MIL standard instead of the ISO10110 standard). Furthermore, certain parameters are sometimes missing on technical drawings.

To support you in such situations, PanDao offers the ***free PRO-OPTIC-CONVERTER*** tool, which covers currently the following topics:

Issue	Description of the mathematical PRO-OPTIC-CONVERTER tool
Slope to mid-spatial-wavelength converter	Reads in the midspatial tolerance in terms of max. slope allowed [minutes] and converts this into the maximum allowed mid-spatial-wavelength [mm].
Radial tolerance to power converter	Reads in the radial tolerance (delta R in [mm]) and converts this into power (the “A” of 3/A(B) in ISO10110 in [fringes])
Determination of asphericity	Reading in the absolute aspherical shape, the asphericity is determined: the maximum vertical distance between the asphere’s surface and its removal sphere.
Determination of the radius of the enveloping spherical surface of an asphere (the removal sphere)	Reading in the absolute aspherical shape, the radius of the enveloping spherical surface (the removal sphere) of an asphere is determined. The enveloping spherical surface is located above the aspherical surface without intersecting the asphere; this spherical surface is located as close as possible above the asphere enabling minimum volume removal during production.
Determination of the smallest radii of curvature (ROC) of aspheres and freeforms	Reading in the absolute aspherical shape, the overall smallest ROC as well as the smallest ROC of the concave parts of the surface are determined.
Edge Tickness Variance (ETV) to decenter (4/) converter	Reading in edge thickness variance (in millimeter), the decentering of the two lens sufaced is being determined (4/ in Minutes)
Find substitute material for PGM	This tool allows you to finda substitute glass with minimum delta in refractive index and that is suitableto beprocessed with precision glas molding (pgm): for details, please consult the “PanDao Master Class” section.
Convert optical surface shape description from *Zernike polinomials* to *power series description*	Input your Zernike polinomial with amplitutes per Zernike term and convert it by one ckick to the ISO10110 shape accuracy description given by 3/A(B,C)

PanDao's *ΔT-Pop rule of thumb*: Optical contacting: determine the maximum temperature change an optical contactes doublet can endure	Input detla alpha of the two glasses which are optical contacted and get information about the delta in temperature at which this doublet will start to get separated by mechanical tension introduced by temperature change.

Check the PRO-OPTIC-CONVERTER out at:



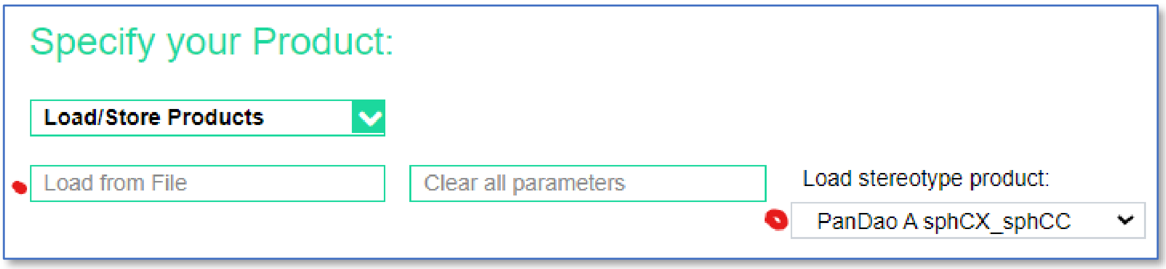
How do I input lens parameters into PanDao?

To run a PanDao analysis to determine the optimal fabrication chain for your lens, you need to enter the parameter values and tolerances of your optical element on the PanDao website.

There are five possibilities of doing this:

a) Read-in the lens data saved by your optics design software. For a list of optical software tools that implemented an option to save your optics data explicitly for PanDao: Please consult the development stage at the end of this manual.
b) Read-in the lens data saved by PanDao (saved by "Download lens to file")
c) Read-in the PanDao Report, a pdf file saved by PanDao (saved by using "Download report pdf")

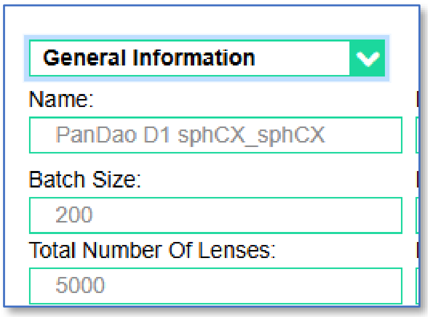
d) load one of the stereotype lenses and change its values and tolerances to the ones you need,



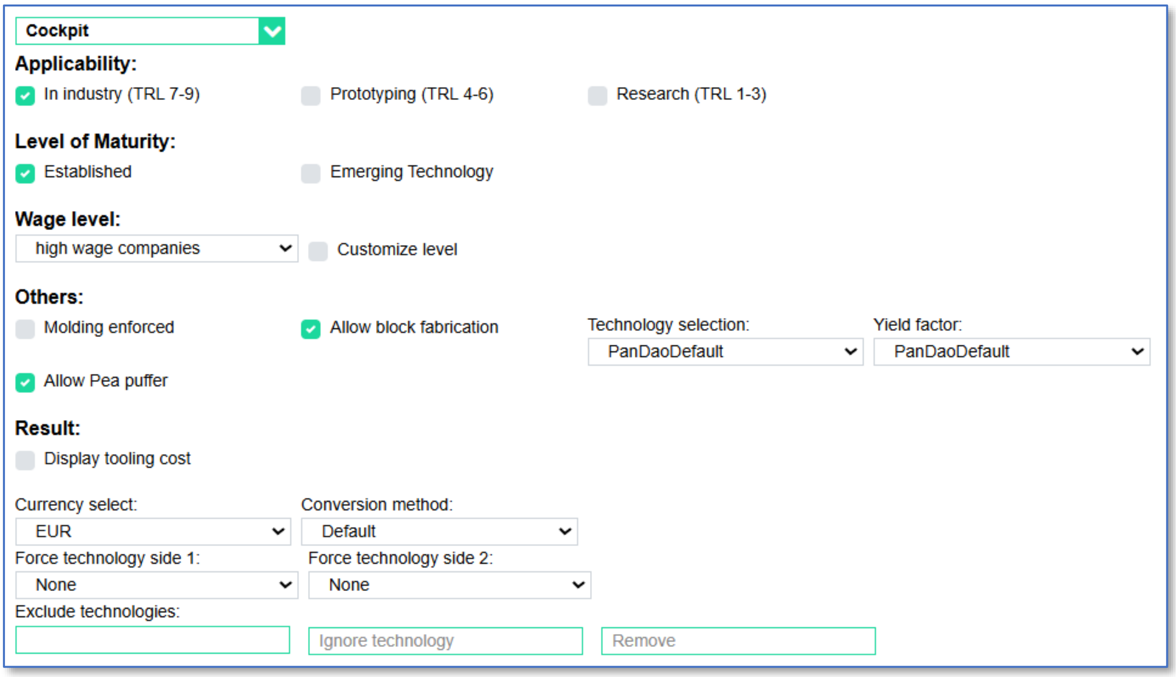
e) enter the values and tolerances of your optics directly by hand

How do I set up lens the PanDao cockpit for my lens?

After having specified your lens data, you need to set up the **PanDao cockpit** parameters to determine the way, PanDao should identify the optimum fabrication chain for your optics.



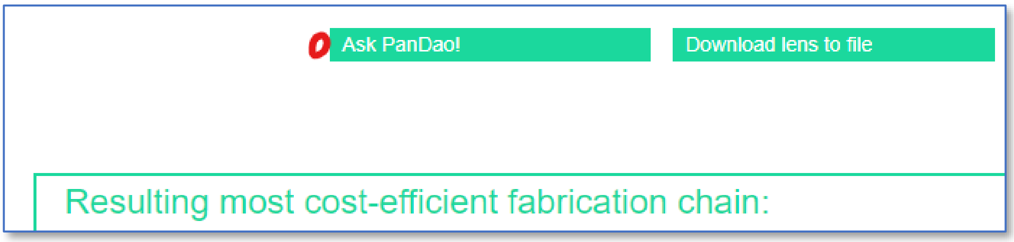
- in the general information section, the total number of lenses to be produced and the batch sizes to be used for delivery (located in the general



- in the general information section, the total number of lenses to be produced and the batch sizes to be used for delivery (located in the general
- TRL level allowed for the 360 optical fabrication technomogies to be considered: TRL123, TRL45 and/or TRL789,
- yield level required
- maturity allowed for the 360 optical fabrication technomogies to be considered: technologoes fully available “in industry” and/or “emerging technologies” (not yet standard in industry),
- wage level for the absolute cost calculations: high, medium or low wage companies.
- select the currency you want to be displayd (PanDao upgrades daily currency conversions)
- select which (if any) optical fabrication technologies (OFTs) you want to exclude
- select which OFTs you want to enforce (only possible if you installed a “digital sister” for your company)
- Set-up if you want to allow pea puffer technology, block fabrication or if you want to enforce moulding as fabrication solution

How do run the PanDao software tool to determine the best chain?

After having specified your lens data and having set-up PanDao's cockpit, you are now ready to start PanDao by clicking on "ask PanDao" and get the optimal manufacturing chain for your optics at minimum cost and manufacturing risk.

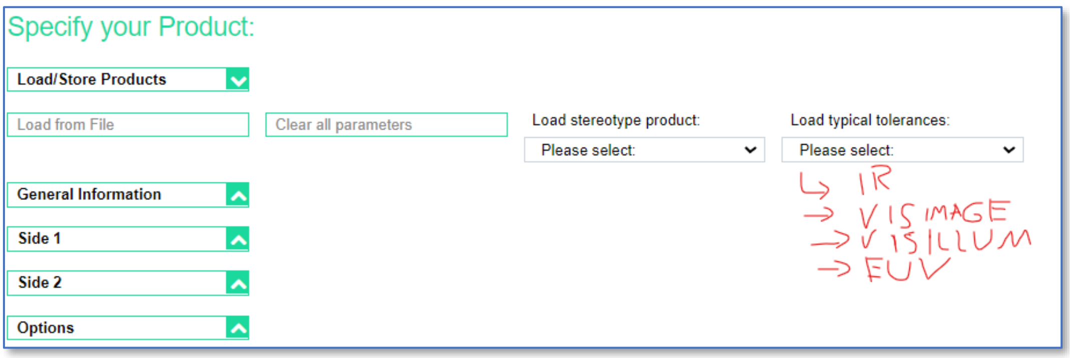


Can I upload typical IR, VIS and EUV lens tolerances into PanDao?

To facilitate the introduction and testing of lenses with typical IR, VIS or EUV tolerances (depending on the wavelength of the light to which they are applied), PanDao offers 4 typical sets of lens tolerances that can be used as a STARTER KIT, which can be uploaded by using the "upload stereotype lens tolerances" button.

- IR: infrared wavelengths optics
- VIS_Imaging: imaging optics at visible light
- VIS_illumination: illuminating optics at visible light
- EUV: extreme ultra-violet lavelengths optics

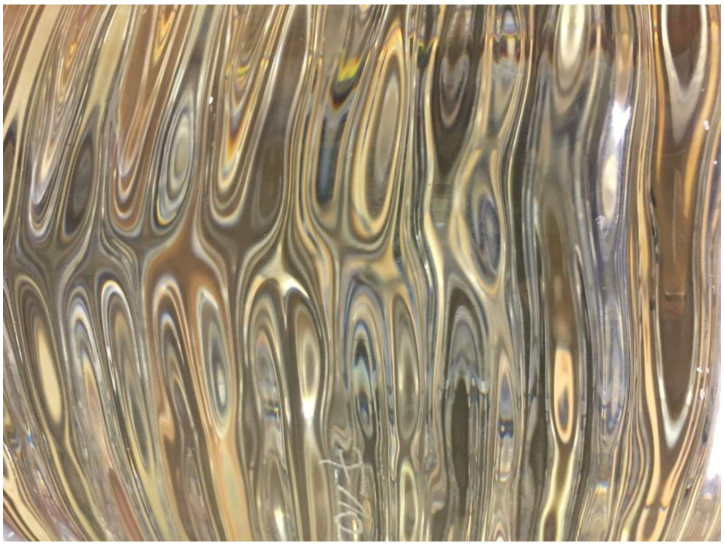
^



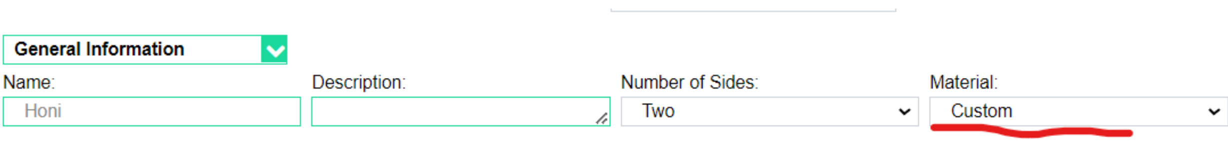
What types of workpiece materials are covered by PanDao?

PanDao is linked to more than 8 optics materials catalogues from the top material providers in optics. A complete list of workpiece materials (such as organic glasses, mineral glasses, IR materials, molding materials, and metals) as well as the glass catalogues currently linked to PanDao, see chapter5 of this manual: "development stage".

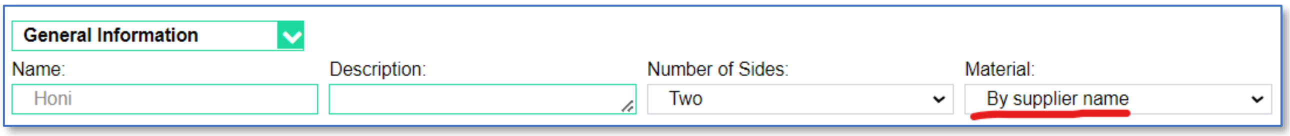
How do I input workpiece material into PanDao?



Choose workpiece material in the general section. There are two choices: you can either select materials by choosing "Custom"



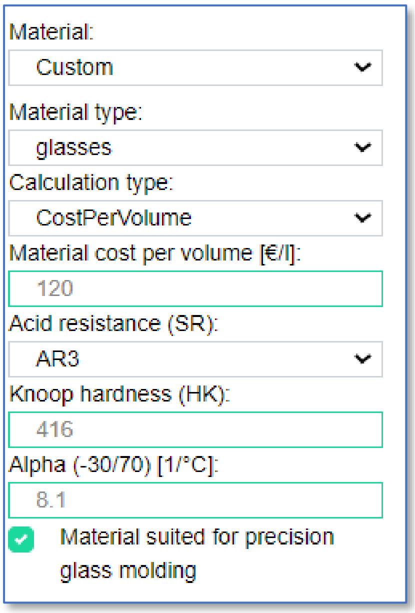
or by choosing "By suppliers name"



If "By suppliers name" is selected, you type in the brand name of the material wanted (e.g. N-BK7, LAK9G15, K-PSFn214P or SCHOTT RealView® 2.0) and PanDao collects all needed material characteristics including material cost from the material supplier's catalogue; currently more than 8 optics materials catalogues are linked to PanDao (see chapter5).

Please note that PanDao does not support the entry of material's no longer provided by suppliers. For example, BK7 from Shott contains lead which is forbidden to use in the EU because of ecological reasons. It is no longer available in the newest catalog and therefore not supported by PanDao. If you want to use PanDao with a material not listed anymore please use the customer material option and enter the values for your material yourself.

If "Custom" is selected, PanDao will ask you to input the essentially needed data including material cost.

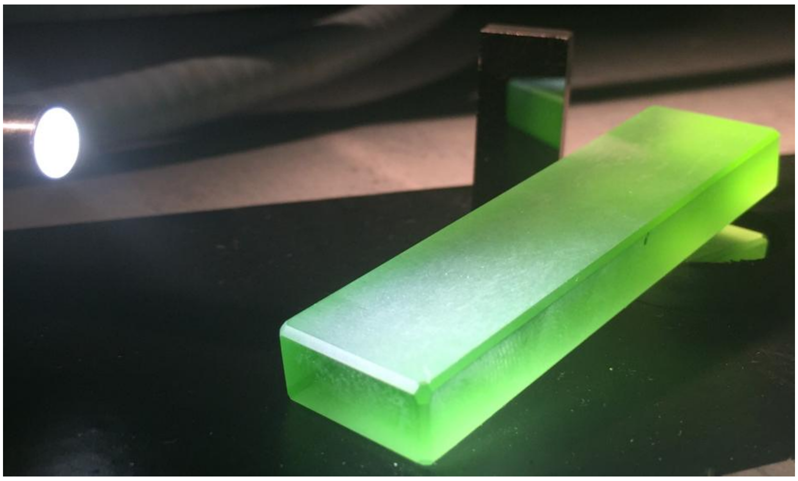


How can input a production situation using pre-purchased blanks as starting point?

Please select “Custom” in the materials section and enter then the cost per blank. PanDao will take this cost per optical element into account and will also take the overproduction needed into account which depends on the yield set up in the “Cockpit” section (e.g. at 50% yied level a production of 20 lenses is needed to have 10 lenses ready to be shipped.

What should I do If my lens material is not listed in PanDao’s material scroll down menus?

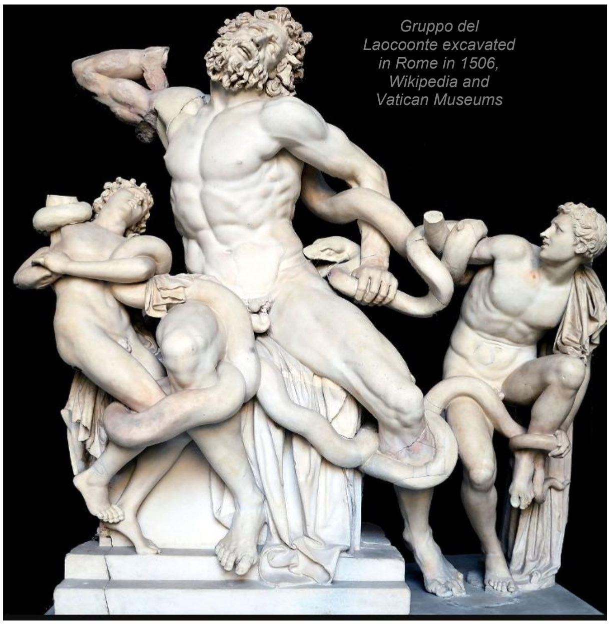
Please check if the material is part of a PanDao material group like e.g. metals or crystals.



If not, contact us at info@PanDao.ch and we will help you.

How do I determine workpiece material cost in PanDao?

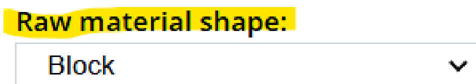
The selection of a suitable blank for optical manufacturing is similar to that of the sculptor who already saw the Laocoon group in the block of marble he wanted to use and only had to uncover it.



Optical elements consist of many different materials (from PMMA to sapphire), have different dimensions (e.g., diameters from a few micrometers to several meters) and geometries (from planar plates to freeforms to conformal optics). Thus, the selection of a suitable blank is challenging and diverse, and, among others, the following blank variants exist:

- cut blocks from a melt
- purchase of a whole glass melt
- grow a crystal
- bar stock for cutting to length
- cylinders for direct rough shaping
- spheres, gobs, semi-finished products (e.g. for PGM)
- powdered or liquid workpiece blank (e.g. for injection molding, 3D printing or coatings).

Currently, PanDao's first fabrication step is rough shaping of surfaces (or molding) depending on the "Raw material shape" selected PanDao will ether start from a plano-parallel pill or block.The size of which is determined by PanDao adding to the optics geometry the required fabrication removal heights needed.



Alternatively, it is possible to start fabrication from pre-purchased blanks. In this case please enter in the custom section of materials the cost of your purchased blank.

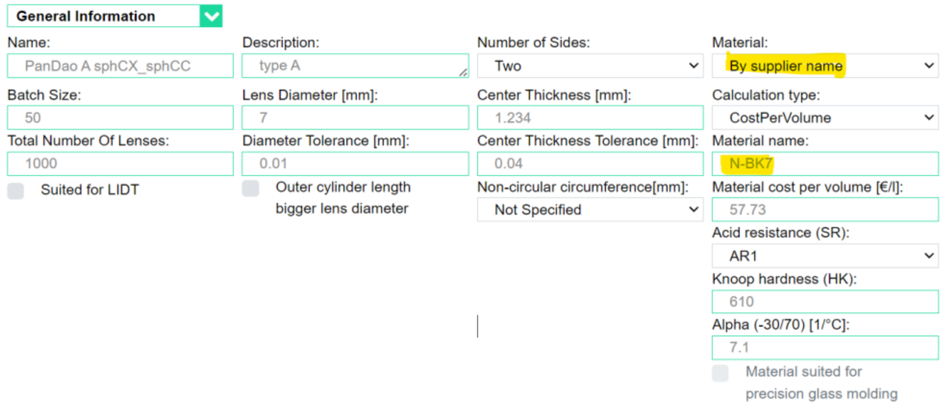
PanDao allows three methods of entering material costs. First use the selector "Calculation type" to determine which input data should be used: Cost per volume [€/l], cost per weight [€/kg] or cost per blank. If cost per weight is selected also the density must be provided.

PanDao takes into account various fabrication process related issues such as the material to be removed and debris caused.

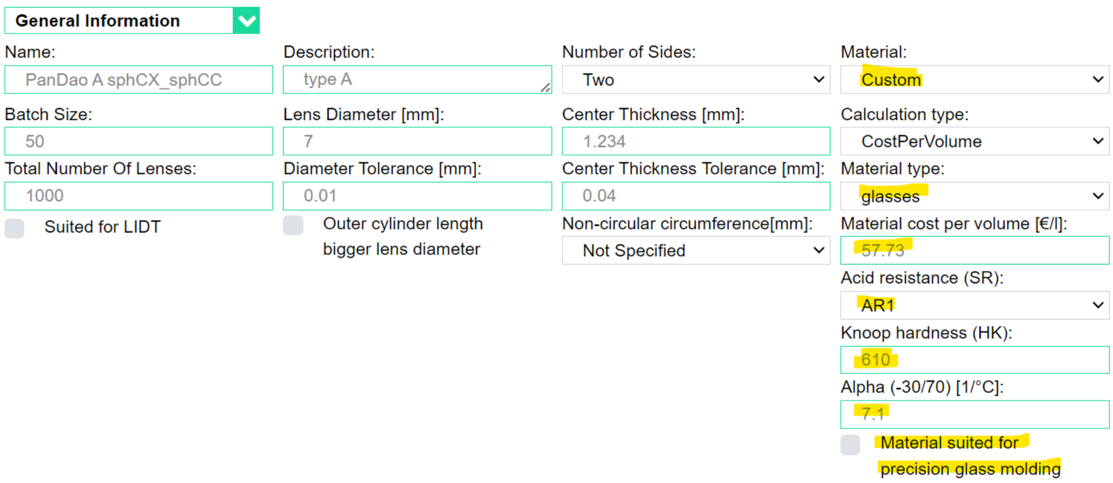
Due to the huge variance in selecting blank geometries, the material cost currently determined by PanDao represents an industrial-realistic benchmark that might be undercut: sometimes.

There are two cockpit to enter the lens material into PanDao:

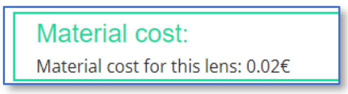
b) either by entry of the ***supplier's glass material's name***, such as e.g. N-BK7. Please note:
   - to select this material type by a scroll-down menu,
   - that PanDao automatically knows if this material is being suited for precision glass molding (PGM),
   - that PanDao automatically collects material costs (per volume) from the supplier's website;



c) or by ***custom*** entry from a scroll down menu. Please note that
   - in this case PanDao requires for glasses the entry of the Knoop hardness (HK) and of the acid resistance (AR) values. This data can easily be found in the internet from the relevant technical data sheet, e.g. N-BK7 with HK = 610 and AR = 2,
   - in this case you need to specify if a glass material is suited for precision glass molding (PGM) or not,
   - in this case have to enter material cost per volume by yourself.

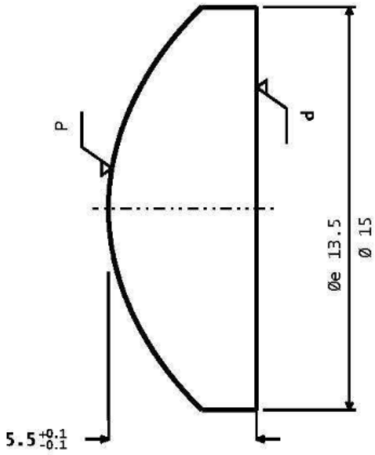


In either case, PanDao will determine material cost of your lens:



How do I enter diameter tolerance and center thickness tolerance into PanDao?

Diameter tolerance and center thickness tolerance is entered as an absolute value into PanDao. For example, in this drawing:



Center thickness tolerance is +0.1 to -0.1 so 0.2 needs to be entered into PanDao. The diameter tolerance works analog it.

How do I enter 4/ centering tolerances into PanDao?

According to ISO10110, PanDao accepts currently the following centering tolerances of a lens. For each side of the lens you can enter 4/ centering tolerances: for flat, cylindrical and spherical surfaces this is specified by tilt only and for aspheres and freeforms it takes an additional “lateral decenter” to fully specify 4/.

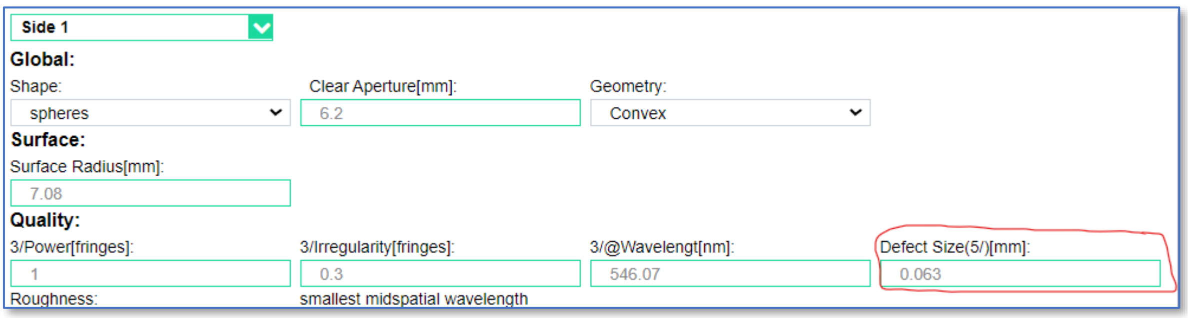
Please note, that if you specify 4/ for both sides of the lens you specify the centering of the surfaces to the outer cylinder of the lens and if you specify only one side of the lens then this is the tolerance with respect to the other side of the lens.

How do I enter defect size (the Scratch/Dig from Mil standrad) into PanDao?

The ISO10110 standard allows maximum defect sizes on the side to be generated in terms of 5/y*x, with

- “x” describing the edge length of a square representing the defect size: e.g. 5/0.016 means that defects with an area of 0.016mm*0.016mm = 0.000256 mm^2 are allowed. Their lateral shape might be a square or a rectangle or any other shape.
- “y” is the maximum number of defects “x” allowed.

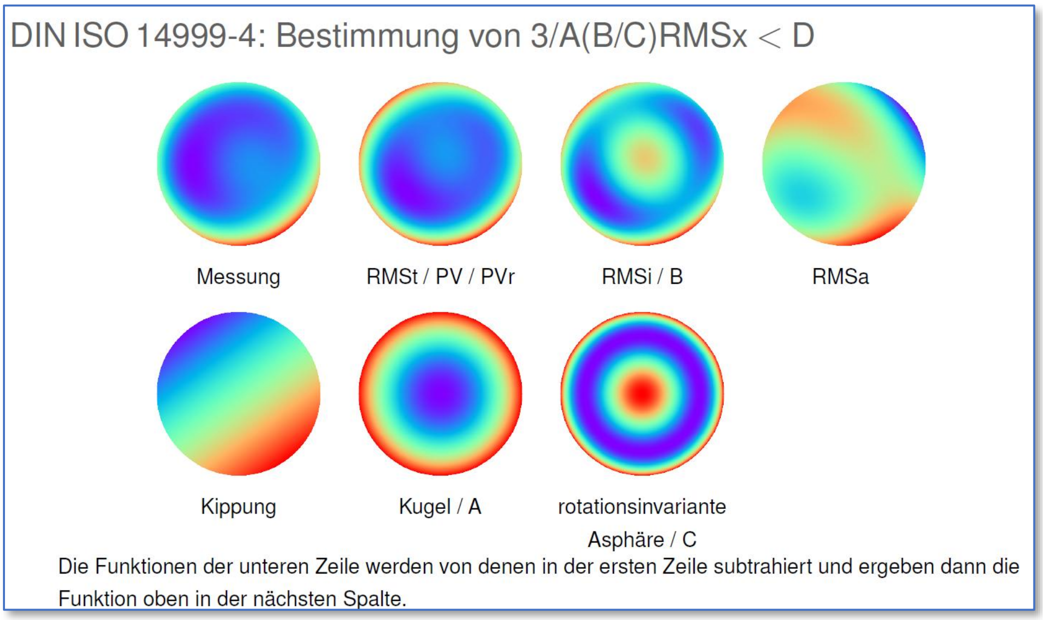
PanDao currently reads in the maximum defect sizes "x" on the side to be produced (5/x). The number y is not needed, since "x" impacts on the determination of the optimal fabrication chain, while "y" impacts only on the quality of handling of machinery, tooling and the cleanliness along the fabrication chain.



How do I enter 3/ shape accuracies into PanDao and what is the contribution of Zernike terms?

PanDao accepts currently (as described in ISO10110) shape accuracies in terms of **3(A(B/C)** with

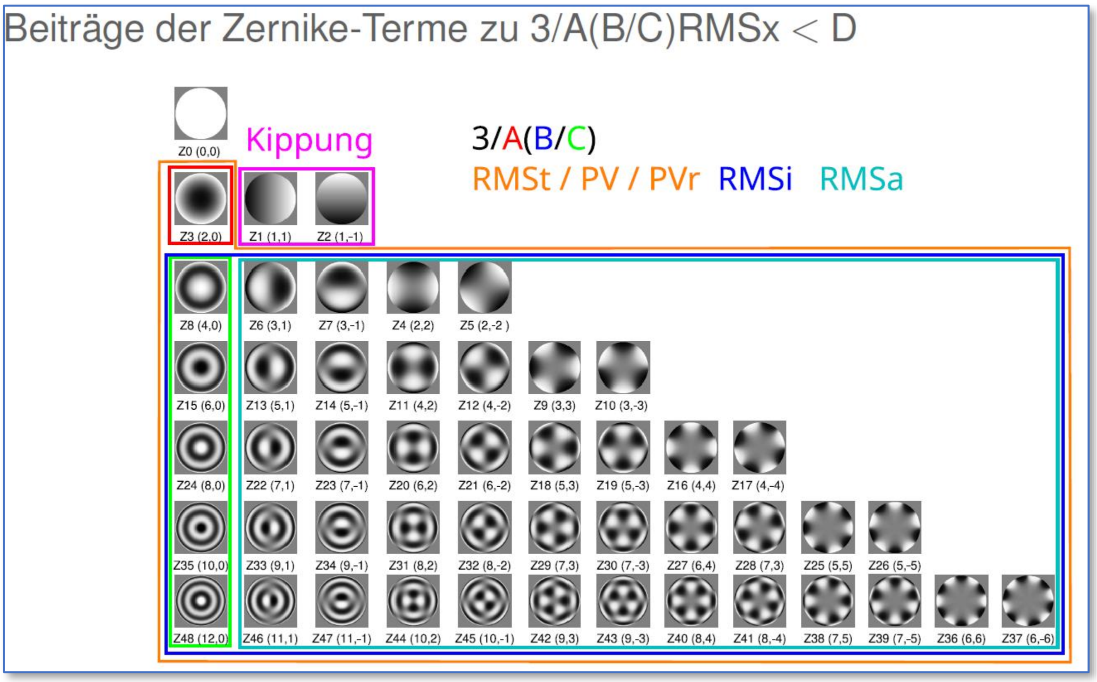
- "**A**" being the power tolerance (power error to best fit spherical surface),
- "**B**" being the irregularity: the deviation from the best-fit-spherical surface and
- "**C**" being the rotationally invariant tolerance (symmetric irregularity error to best fit asphere to B)



Many thanks to Eckhard Langenbach, 2025

Input is the measurement (Messung). From this we substract the Wedge (Kippung) and obtain the RMSt/PV/PVr. Substracting the spherical part (Kugel/A) results in the RMS/B and extracting from that the rotational invariant part C results in the RMSa error of the surface unter test.

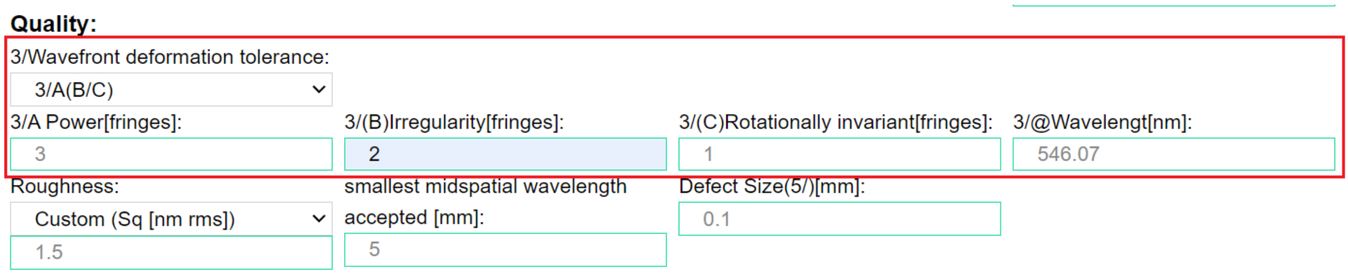
The following figure shows the relationship between the shape deviations A, B and C (and RMSt, RMSi and RMSa: see figure above) on the one hand and the respective Zernike terms contributing to them on the other; e.g, Z3 of the error = spherical error or A:



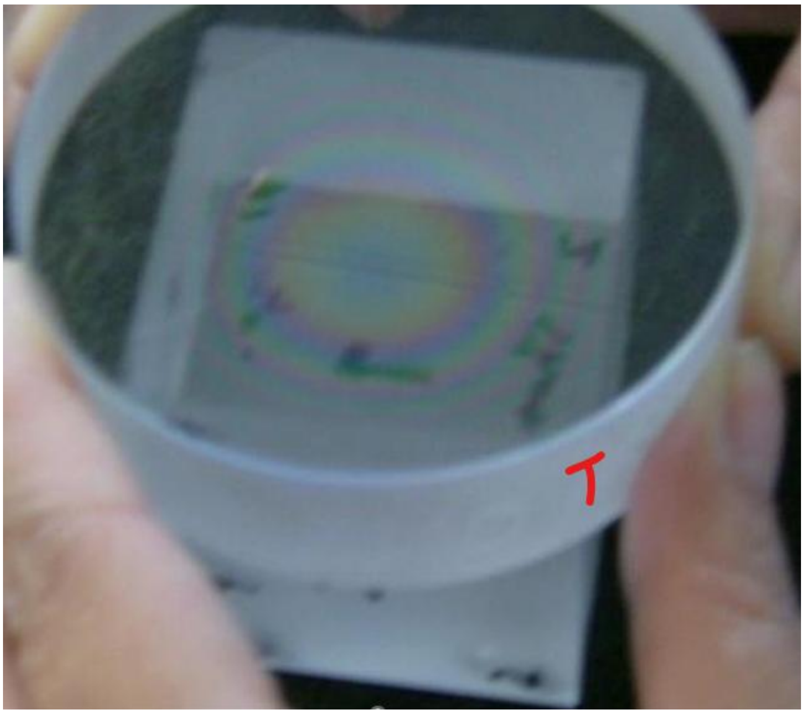
Many thanks to Eckhard Langenbach, 2025

Contributions of Zernike terms towards A, B and C shape errors

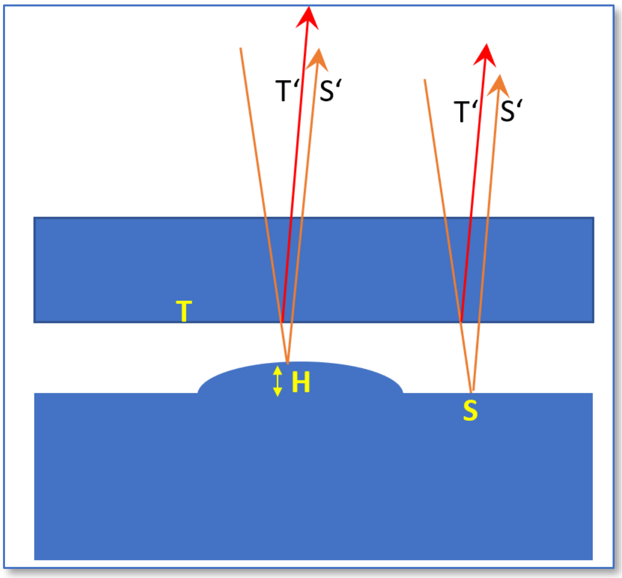
With the “Wavefront deformation tolerance” at the PanDao input window selected, you can choose which one of the three parameters 3/A(B,C) you want to specify.



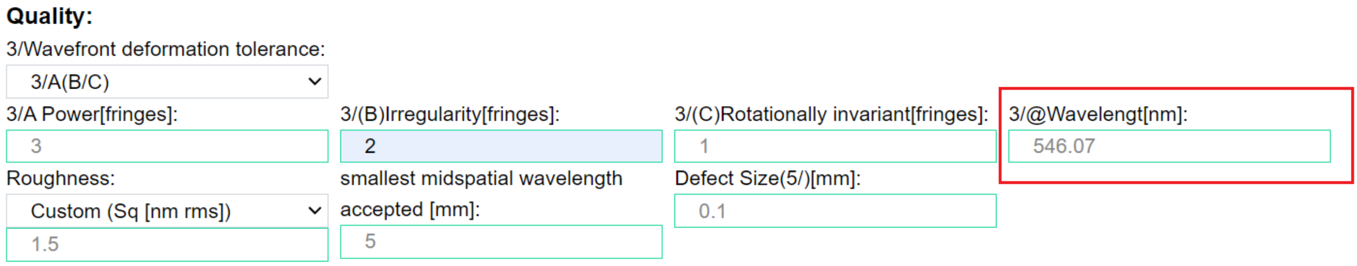
The units are fringes, wave (not surface), an approach derived from the ancient technique of measuring shape deviations using test plates (T) produced by master opticians hand polishing (a testing setup also found in Fizeau interferometers):



The shape error (surface height H) of the surface under test (S) is measured by comparing the shape of surface S with the perfect (usually < 1/20 lambda shape accuracy) and identical shape of surface T of the test plate. This is done by interfering the light rays T' and S'. Consequently, a height deviation H of the surface S appears in the interferogram as 2*H.(=wave).



As a default, PanDao reads in shape accuracy 3/A(B) measured at 546.07nm wavelength. The 546.1 nm line is a green emission line of mercury. Before the invention of the laser, it had commonly been used in various applications, including optical testing, alignment, and calibration.Typically, the mercury vapor lamp, which is a discharge lamp containing mercury, is used as a light source to produce these emission lines. When the mercury vapor lamp is electrically stimulated, it emits light at various wavelengths, including the green line at 546.1 nm. According to ISO10110, PanDao allows the setup of any other test wavelengths by simply adjusting the entry in field 3/@lambda:



Quality:

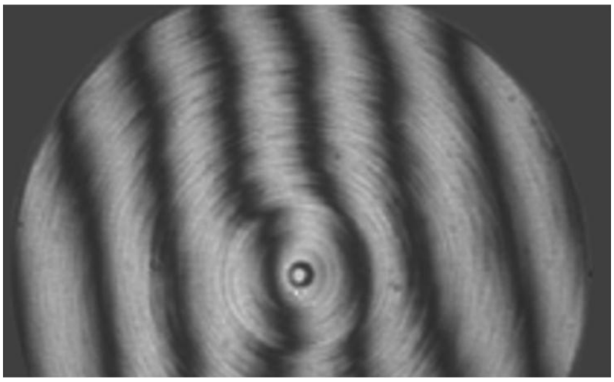
3/Wavefront deformation tolerance: 3/A(B/C)

3/A Power[fringes]:	3/(B)Irregularity[fringes]:	3/(C)Rotationally invariant[fringes]:	3/@Wavelengt[nm]:
3	2	1	546.07
Roughness:	smallest midspatial wavelength accepted [mm]:	Defect Size(5/)[mm]:	
Custom (Sq [nm rms])	5	0.1	
1.5			

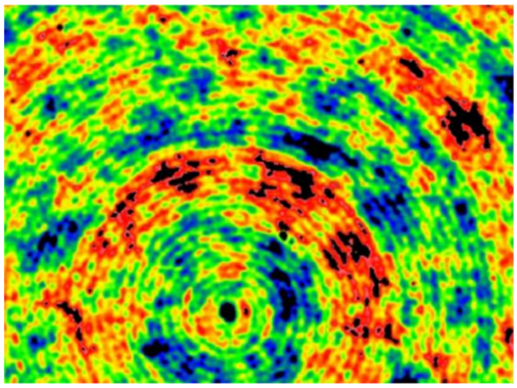
As an example given, a hight deviation H of the irregularity B of 1 micron equals B = (1000/546.07)*2 = 3.66 fringes; and if we assume a power error of 2 micron height the shape accuracy of this surface equals **3/7.32(3.66).**

How do I enter midspatial tolerances into PanDao; what is the “smallest midspatial wavelength”?

Midspatcial waves (MSW) on a 6400 km radius planet

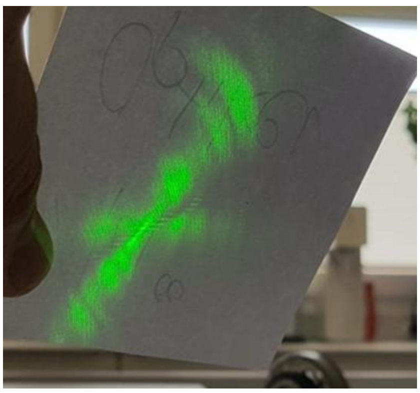


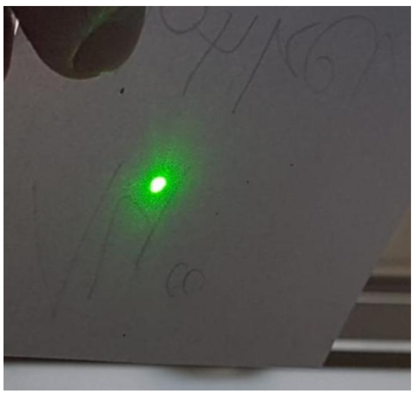
The non-straight edges of the fringes are caused by midspatials of a suboptimally set up cnc polishing process



Concentric midspatials on an pre-polished optic caused by a suboptimally performed point contact cnc grinding process

Midspatial surface errors are located along the Power Spectral Density plot (PSD: a measure for how many spatial freqencies are present on the surface) between the low frequency shape errors and the high frequency roughness errors. As a rule of thumb midspatials "start" at surface wavelengths that are smaller than about a 5th of the clear aperture. Midspatials are responsible for miss-led light rays, unwanted lateral brightness destributions within the generated image or may cause scattering effects or halos.





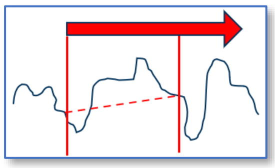
Focus of a lens with midspatials present *Same lens focus with removed midspatials*

Typically, optical midspatial shape errors origin from:

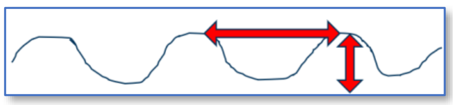
- machine vibrations
- sub-aperture tool contacts
- removing a lot of material during sub-aperture polishing
- alignment of coordinate systems of testing and machining
- resonace frequencies of machines and tools
- fixed ratio w-tool to w-workpiece
- quality of CAD data files generating CNC machining files (e.g. splines and NURBS)

Among the multiple ways to specify midspatial tolerances of an optical surface, two are most common: SLOPE and Mid-Spatial-Wavelength (MSW).

- SLOPE specifies a maximum allowed local inclination [minutes] (usually, but not necessarily for a defined sampling length):



- MSW specifies the smallest allowed midspatial wavelength [mm] while the maximum allowed amplitude depends on the shape accuracy tolerancing:

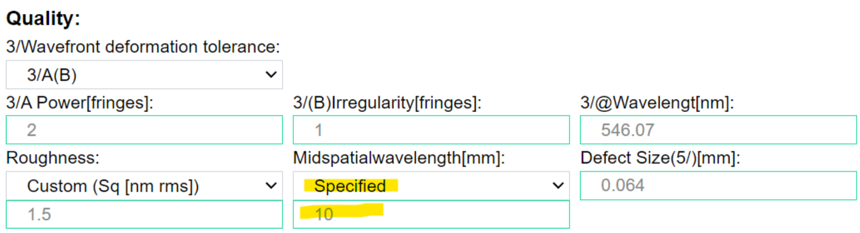


Both (SLOPE and MSW) can be converted into each other using PanDao's "PRO-OPTICS-CONVERTER" tool (see relevant chapter of this manual and www.PanDao.ch).

PanDao reads in MSW:

- Please select if Mid-Spatials are specified, not specified or not allowed here:

- If specified please input the Mid-Spatial-Wavelength in mm here:

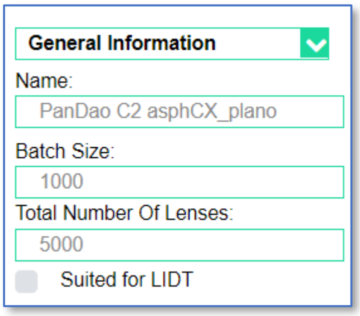


- the maximum allowed amplitude of the MSW depends on the values of the shape accuracy tolerances (3/A(B,C) and has not to be specified as PanDao deals with this automatically.

Typically, no midspatials are allowed for flat and spherical surfaces, which corresponds to MSW=0.

How do I select if my lens should withstand a high level of Laser Induced damage Threshold (LIDT)?

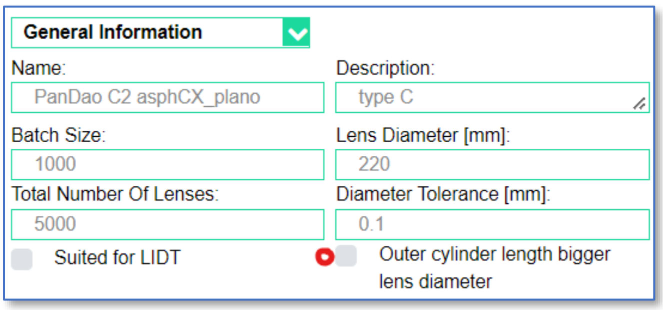
Please select “suited for LIDT” to determine lens fabrication chains for lens intensity levels of up to appr. 30 J/cm^2. Please note that PanDao does not evaluate if the chosen lens material is suited for LIDT.



How do I input a rod lens into PanDao?

Fabrication chains for rod lens generation have special characteristics and rules.

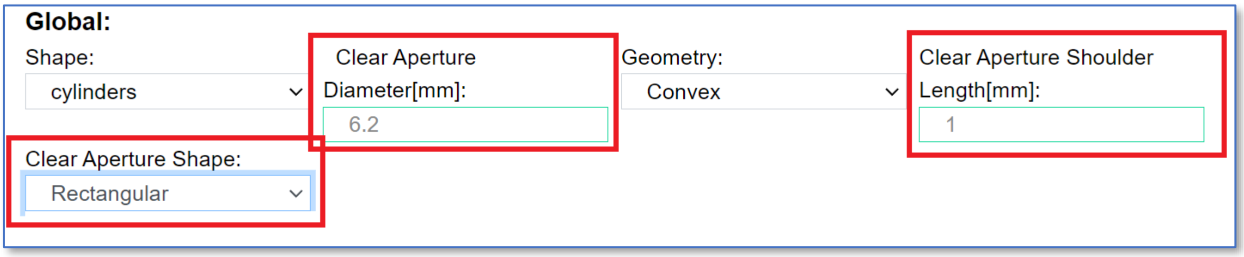
Please notify PanDao at:



Please note that for rod lenses currently no block fabrication is considered.

How do I input clearaperture for cylinders and freeforms into PanDao?

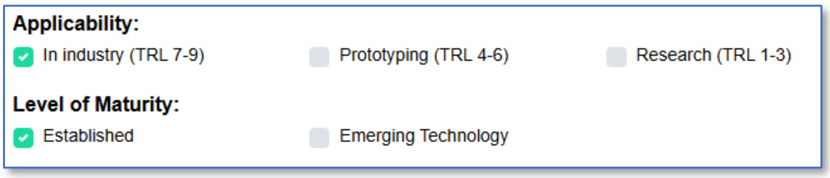
For cylinders and freeforms the clearaperture can ether be circular or rectangular. For circular clearapertures only one parameter is needed. For rectangular openings the diameter and shoulder length must be specified:



How do I select the TRL level of Optical Fabrication Technologies to be considered by PanDao?

PanDao determines the optimal fabrication chain for a given lens. It distinguishes between technology readiness levels (TRL) of 360 optical manufacturing technologies.

The following selections can be made for the Optical Fabrication Technology Techniques (OFTTS) to be considered by PanDao:



What is block fabrication and how do I select or omit this option?

Block fabrication is a parallel machining process where multiple workpieces are machined with one mount at the same time. This process is appliccable for e.g. precision glass molding or injection molding using multiple inserts in mold-dyes or waferlevel molds. Other applications are e.g. double sided lapping or double sided polishing using workpiece cages and planetary movements within the machines polishing zone. Traditionally, block fabrication applies for flat surfaces or spherical surfaces with big-enough radii with typitcal examples such as prism fabrication or spherical lenses for endoscopy applications.

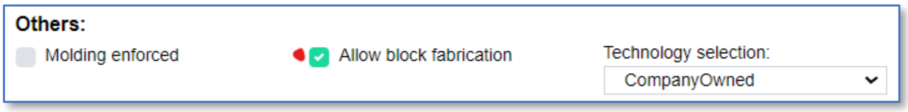
Whenever possible (e.g. if lens spherical radius is much bigger than lens diameter which includes flat surfaces), PanDao considers block fabrication where a multiple samples holder is used to machine in parallel instead of sequentially: E.g.:

The comparison of block fabrication over single piece sequential fabrication is done per each step along the fabrication chain. It is a cost trade-off

- between one production run generating many lenses at the same time requiring large tools, mounts and a more complex workpiece assembly,
- versus a much faster fabrication step, smaller tools, less mounting effort but a whole machine busy for only one lens.

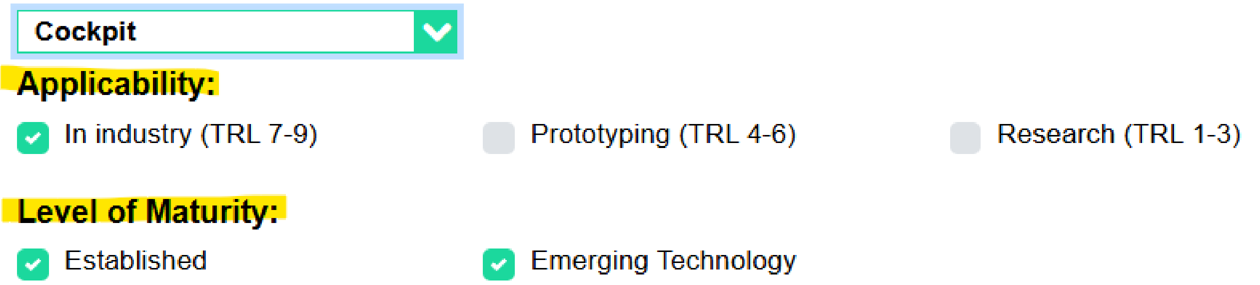
Please note, that during block fabrication while applying traditional methods such as double sided lappping or overarm polishing or cnc polishing, the surface quality is generated over the whole workpiece surface per definition of the fabrication set-up. Therefore, the clear aperture diameter has almost no impact on cost; the major cost driver is the lens diameter.

Block fabrication can be switched on and off in the cockpit section:



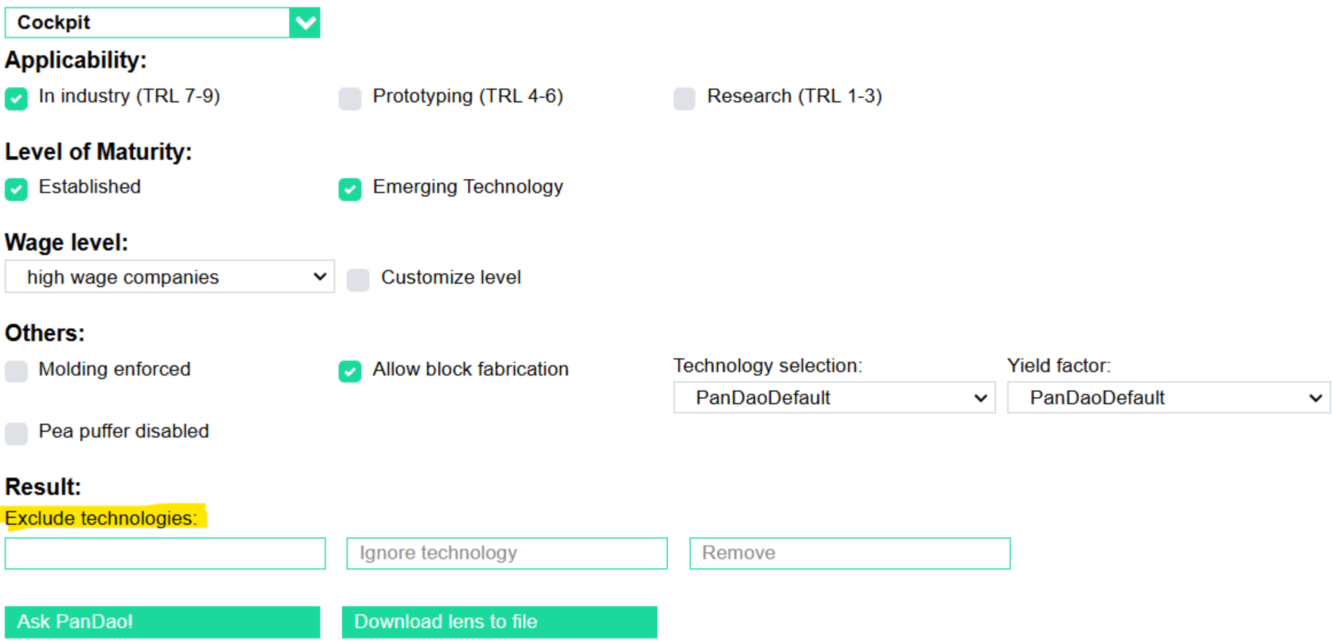
How do I select or omit Optical Fabrication Technologies (OFTs) to be considered by PanDao?

Select the characteristics of Optical fabrication Technology Techniques (OFTTs) in the Cockpit section of PanDao by using the two selection criteria "Applicability" and "level-of-Maturity":



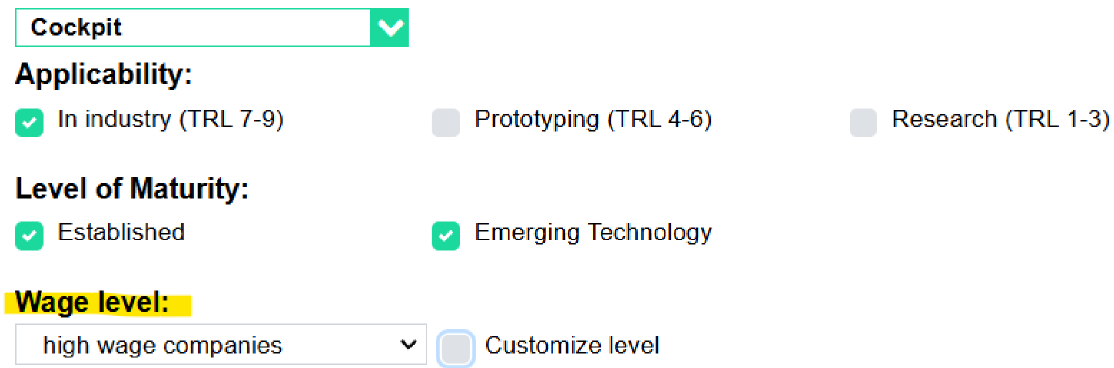
a) ***Applicability***: in the cockpit section of the input surface at least one of the three choices must be activated with a tick: "In industry", "Prototyping" and/or "Research",
b) ***Level-of-Maturity***: in the cockpit section of the input surface at least one of the two choices must be activated with a tick: "established" and/or "emerging technologies".

After you have received information about an optimal fabrication chain for one optical element you can omit one or several of the listed OFTs and start a new PanDao request to build the best chain possible without the selected OFTs available.
In order to do so, please copy and paste the OFT's name from the output into the field "exclude OFTTs" which is located in the cockpit section:

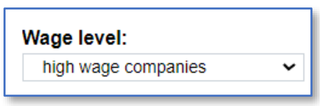


How do I select the correct “Wage-Level” for my lens?

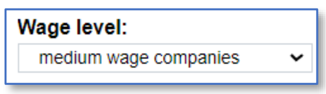
PanDao distinguishes 3 different types of companies: high, medium and low wage level companies. Please note that in every country the wage level might differ and that production qualities not necessarly depend upon the wage levels:



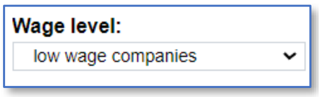
a) **High-wage companies:** e.g. existing in Germany, France, UK, USA, Japan, Singapore, Switzerland, Austria and Italy



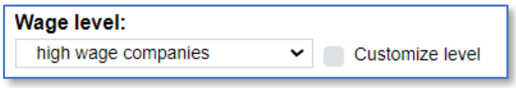
b) **Medium-wage companies:** e.g. existing in Romania, Bulgaria, Turkey, Portugal, Mexico, Taiwan and Serbia.



c) **Low-wage companies**: e.g. existing in China, India, Indonesia and Korea

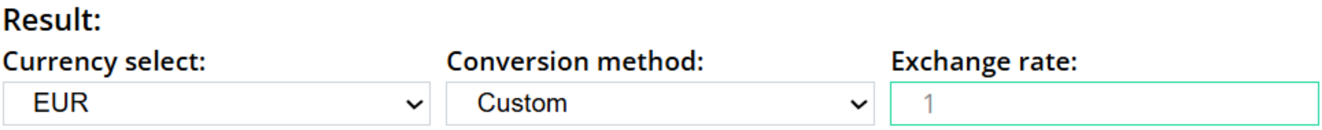


In addition, it is possible to enter one's own commercial conditions by choosing custom input: e.g. bank interest, investment payback time to the bank and salaries of engineers or technicians.



How does PanDao deal with different currencies?

In the cockpit section it is possible to choose the currency:

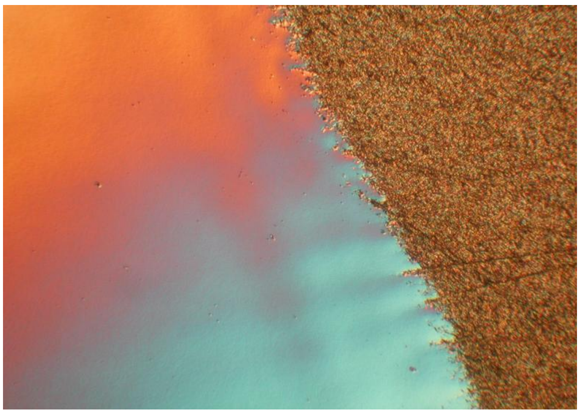


Depending on the currency, select the currency symbols in the inputs and results will change (€, $, Fr.…). The conversion method decides how PanDao deals with exchange rates. If Custom is selected, the user needs to enter the exchange rate from EUR to the selected currency. If Default is used, PanDao will use its internal values. These values are updated every day from: https://frankfurter.dev/

Note that the input data needs to be in the selected currency and will not change automatically when the currency select is changed. For example, if USD is selected the material cost per volume has to be entered in dollar per liter.

What are typical surface roughness ranges and values?

PanDao asks surface roughness values in terms of Sq [nm rms] over a spatial bandwidth of 0.002mm to 0.08mm; derived from DIN ISO 10110-8:

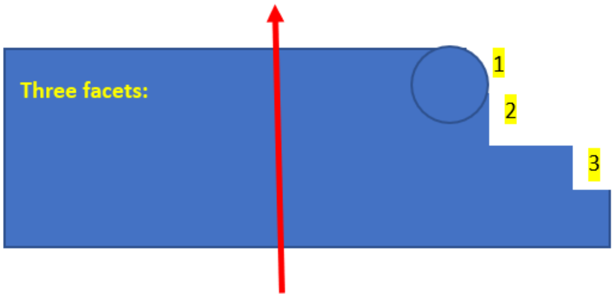


Range	Rq over spatial bandwidth of 0.002 mm to 1 mm
P1	≤ 8 nm rms
P2	≤ 4 nm rms
P3	≤ 2 nm rms
P4	≤ 1 nm rms

What are Facets?

In PanDao, for each optical element the cost for protective chamfers is included in the center grinding cost.

The so-called facet stages are being generated by molding or as a cnc grinding step after the center grinding step has been finished (on the same machine). Facet stages are binary-like step structures at the outer edge of the lens located between the clear aperture and lens diameter to e.g., serve mounting issues of the lens into the objective.



How do I enter Facets?

Choose at a side of the lens the number of facets required, e.g. 3

Number Of Facets:		
3		
Height facet 1[mm]:	Height facet 2[mm]:	Height facet 3[mm]:
0.5	1	0.01
Width facet 1[mm]:	Width facet 2[mm]:	Width facet 3[mm]:
0.2	3	0.1

NumberOfFacets: 3

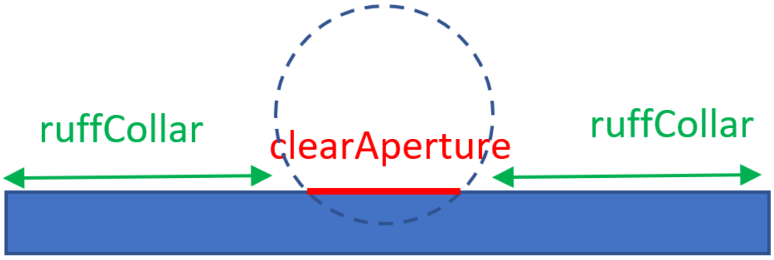
In this case three extra windows open each asking height and length of the facet [in mm].

- For rectangular facet shapes (No.2 and 3 in the picture in the facets chapter): enter the height and width e.g. facet 1: 0.5 mm / 0.1 mm.
- For circular or "axicon-like" chamfers (No.1 in the picture in the facets chapter): enter only their height and depth but neither the radius nor the hypothenuse (of the axicon).

Facet 1:	Height (parallel to optical axis in mm)	Width (rectangular to the optical axis in mm)
Facet 2:	Height (parallel to optical axis in mm)	Width (rectangular to the optical axis in mm)
Facet 3:	Height (parallel to optical axis in mm)	Width (rectangular to the optical axis in mm)

How do I enter plano Facets for spherical lenses?

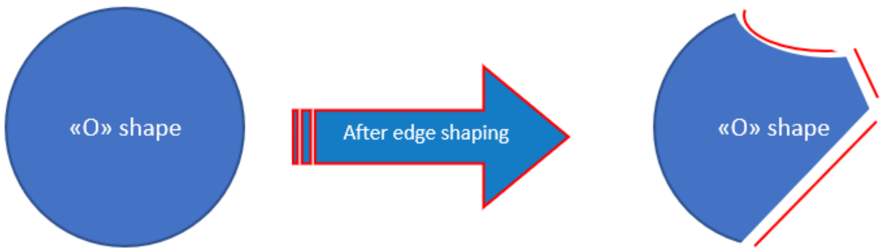
Often, concave, spherical surfaces are being generated into plano paralell plates. In that case, a huge plano facet (called the ruff collar in the picture below) covers the area between clear aperture and lens diameter. Ad extremum, this covers the situation where an hemisphere is being generated with 2 * R < lens Diameter.



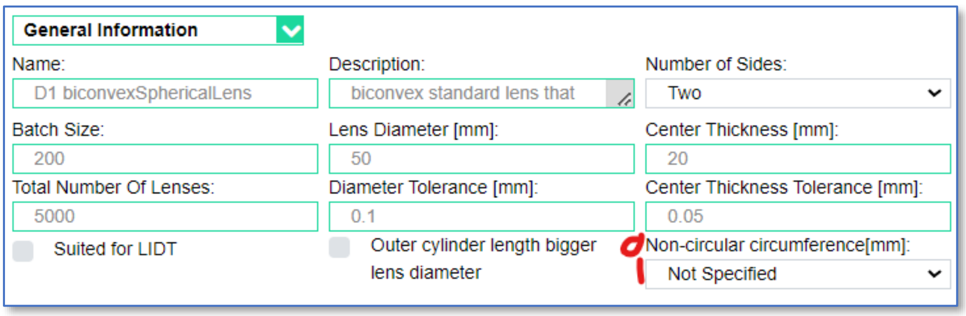
In that case, please describe th efacet with its correct width and a hight removal of 0.010 mm.

What are non-circular perimeters?

For mounting purposes, the outer lens cylinder might have a non-circular shape, e.g. a “D” shape. These non-“O” shaped lens cylinder shapes might be more complex than flat and circular shape segments (visible if the lens is observed parallel to the optical axis (top view)):

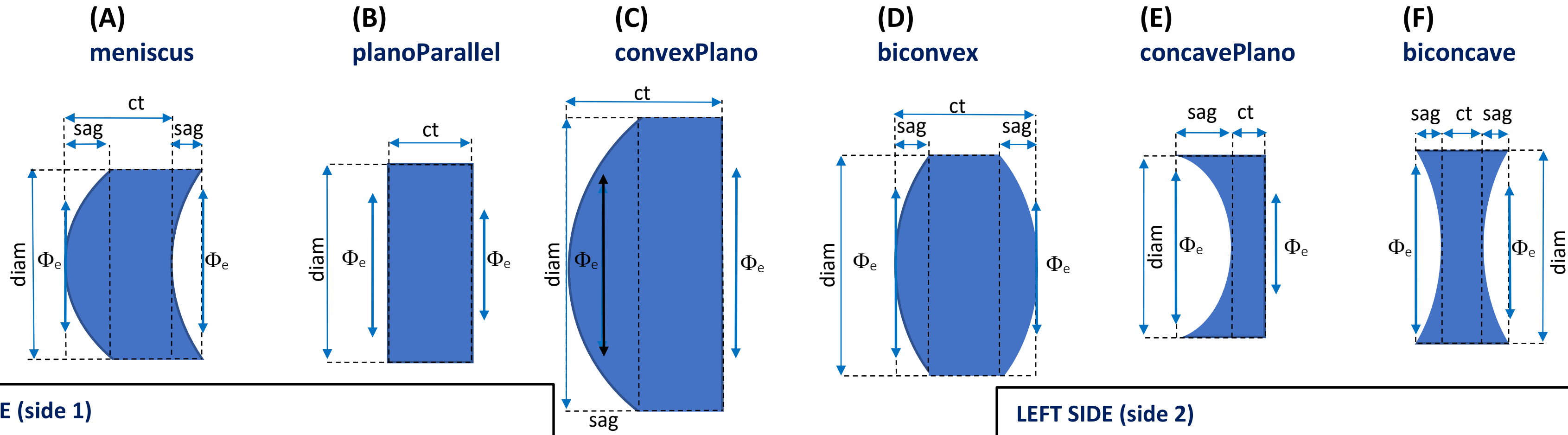


PanDao asks the overall ***non-circular circumference*** length which is the overall length of the non-cylindrical shapes along the lens perimeter as indicated with the red lines in the example above.



PANDAO FROM OPTICS TO FABRICATION

Possible (a)spherical lens geometries and input parameters



LEFT SIDE (side 1)

clearAperture Φe: circle (only for flats and cylinders: circle or rectangle)
prot.chamfer (length)
coating (AR/special)
3/power(irregularity)
4/ (for flats use 3/)
5/
6/ (if > 10J/cm^2 = LIDT)
Sq surface roughness
smallest midSpatialWaelength:
sag

if spherical surface (YES/NO):
R:

if aspherical surface (YES/NO):
smallest radius of curvature
asphericity
radius of removal sphere:
contains concave parts (YES/NO)?
smallest concave radius of curvature (SCRC)

if cylindrical surface (YES/NO):
clearAperture shoulder length Φe:

if off-axis aspherical surface (YES/NO):
see off-axis aspheres section below

if freeform (YES/NO):
see freeformss section below

MATERIAL:

if glass (YES/NO):
HK:
AR:

DIMENSIONS

center thickness ct
(for of-axis aspheres and freeforms: enter local minimum lens thickness)
ct tolerance
lens diameter
diam tolerance

PRODUCTION ORDER

totalNumber pcs
batchSize pcs:
TRL level
yield

LEFT SIDE (side 2)

clearAperture Φe
prot.chamfer (length)
coating (AR/special)
3/power(irregularity)
4/ (for flats use 3/)
5/
6/ (if > 10J/cm^2 = LIDT)
Sq surface roughness
smallest midSpatialWaelength:
sag

if spherical surface (YES/NO):
R:

if aspherical surface (YES/NO):
smallest radius of curvature
asphericity
radius of removal sphere:
contains concave parts (YES/NO)?
smallest concave radius of curvature (SCRC)

if cylindrical surface (YES/NO):
clearAperture shoulder length Φe:

if off-axis aspherical surface (YES/NO):
see off-axis aspheres section below

if freeform (YES/NO):
see freeformss section below

What are the different ways to mount optical elements for manufacture?

In general there are two different ways to hold an optical workpiece for manufacture:

- ***mechanical mounting*** and
- ***optical contacting***.

Mechanical mounting offers roughly eleven different methods for securing a workpiece and can be applied across a wide range of accuracies, materials, and geometries. The most precise of these techniques is vacuum chucking, as used in the mounting of astronomical mirrors, where sub-micron accuracies are achieved over diameters of several hundred millimeters

In contrast, optical contacting is limited to workpieces and mounts made of glass or glass-ceramics with high-quality polished interfaces that adhere through van der Waals forces. This technique is widely used in the manufacture of prisms and, more generally, in precision optical mounting

(A) MECHANICAL MOUNTING

Mechanical mounting refers to any method of holding, supporting, or securing an optical component by physical means rather than by optical contacting. In optics manufacturing, there are about ***eleven*** mechanical mounting techniques existing, relying on mechanical restraint, adhesive bonding, or vacuum forces to maintain the component's position during fabrication, alignment, or testing.

A. Mechanical fixtures and restraints

- ***Clamping*** – securing the optic using screws, levers, or spring clamps.
- ***Kinematic mounting*** – locating the optic precisely on defined contact points.
- ***Screw or lever pressing*** – applying adjustable mechanical pressure.
- ***Shrink fitting or press fitting*** – using thermal or mechanical interference to fix the component.

B. Adhesive and wax-based mounting

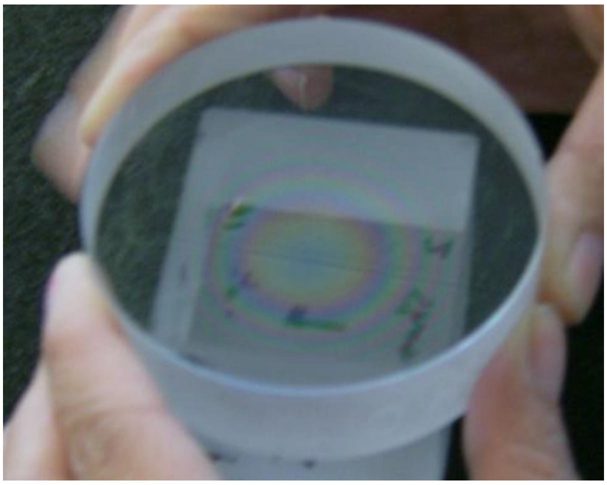
- ***Wax mounting*** – attaching with optical wax, pitch, or shellac for temporary setups.
- ***Adhesive fixing (cementing)*** – using epoxy, UV-curable, or temporary optical adhesives.
- ***Potting or embedding*** – encapsulating in resin for mechanical support.
- ***Adhesive tape mounting*** – temporarily fixing with specialized optical tapes (nicely stress-free)

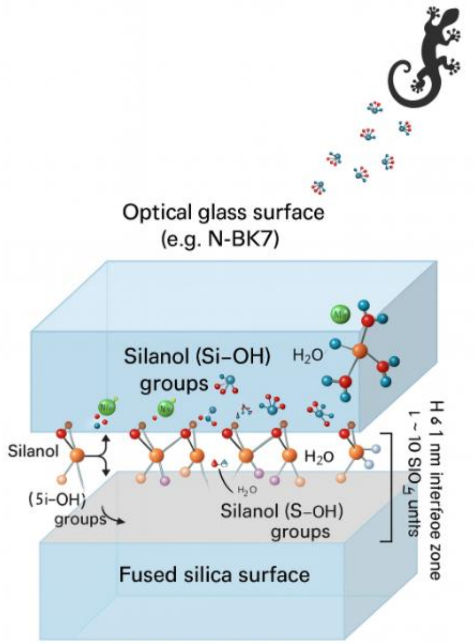
C. Inlay and chucking techniques

- ***Inlay mounting*** – resting in a machined seat or nest, often with a compliant interface material.
- ***Vacuum chucking*** – holding the optic by negative pressure on CNC or ion-beam platforms.
- ***Magnetic holding*** – securing coated or metallic-backed components using magnetic fixtures.

(B) OPTICAL CONTACTING

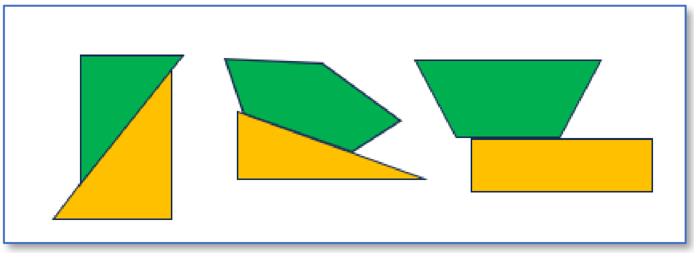
Geckos move effortlessly across walls and ceilings by continuously creating and releasing billions of van der Waals contacts at their feet. At the same molecular scale, optical engineers create similar bonds when two super-polished glass surfaces meet. Their interface, only about 1 nanometre thick, or roughly ten molecules across, is stabilized by the same family of forces: van der Waals attraction and hydrogen bonding between hydroxyl groups on each surface. This phenomenon, known as ***optical contacting*** (ansprengen), allows prisms, flats and other components to be joined temporarily for polishing or interferometric testing.





Optical contacting two glass elements, e.g. a prism and its fused silica mounting strip holder together

There is only one optical contacting method existing for mounting for manufacturing e.g. a prism: The back side of the optical surface to be machined has already been polished and is optical contacted onto a polished glass surface of the mount. That way, the surface to be machined is located horizontically below the polishing tool and ready to be polished.



Cross-section in the z,y-plane of a triangular prism, a penta prism and a trapez prism strip optically contacted to a mounting strip.

PanDao developed a rule of thumb for the temperature difference (to the one where the optical contacting was generated) which is needed to disconnect two glass bodies that have been optical contacted, the **ΔT-Pop Rule**:

$$\Delta T \approx (\tau_c / \Delta\alpha) \cdot (1/E_1 + 1/E_2)$$

Despite the traditional use of flames or deep freezers to separate optically contacted parts, the ΔT-Pop Rule shows that only a few kelvin are usually enough to initiate release of a fresh contact. This rule of thumb is based on about 1 MPa of adhesion distributed across a one-nanometre-thick interface of roughly ten molecules. It demonstrates that a process still dominated by technician experience, and today's standard in the manufacture of high-value precision prisms, can now be approached with quantitative precision, supporting a more careful and engineering-based approach to optical contacting.

Precision and accuracy begins with understanding the subtle forces that bind and release, walking gently like a gecko, even in our optical workshop.

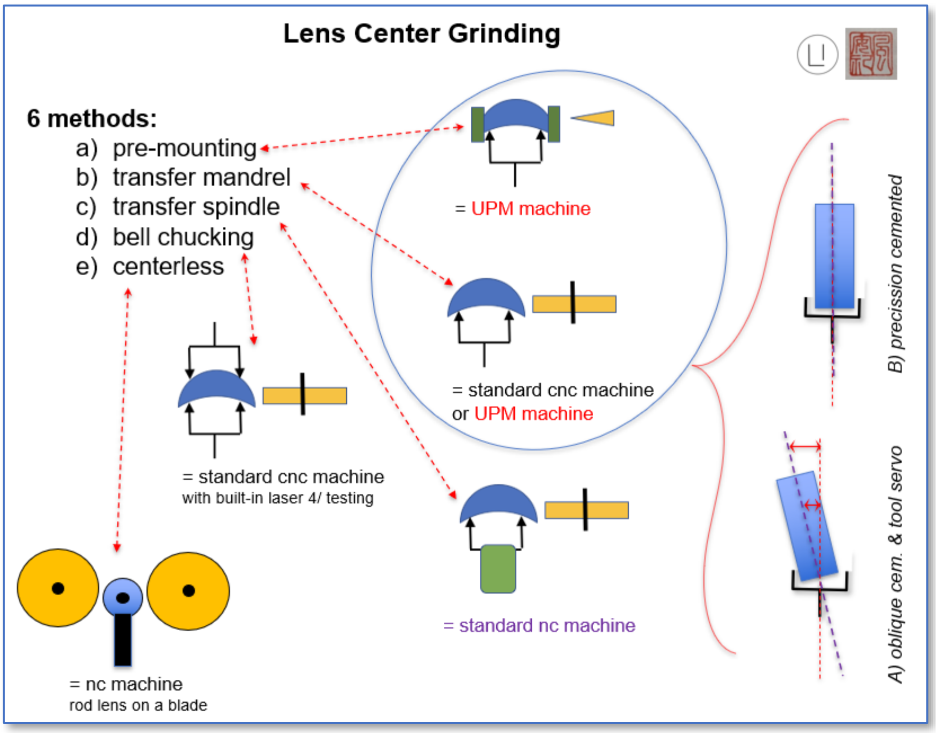
Please consult PanDao's ***PRO-OPTIC-CONVERTER*** to calculate the temperature needed for disconnecting your optical contacted mounts.

How is PanDao handling center grinding of optics?

Center grinding a bi-convex lens by bell chucking.

To achieve the (ISO10110 specified) centering tolerance 4/30'' the outer cylinder of the lens is being machined to become parallel to the axis of the light traveling through the center of the lens.

There are about seven different approaches existing to generate the outer cylinder of an optical element.



Seven approaches to generate the 4/ tolerance of a lens

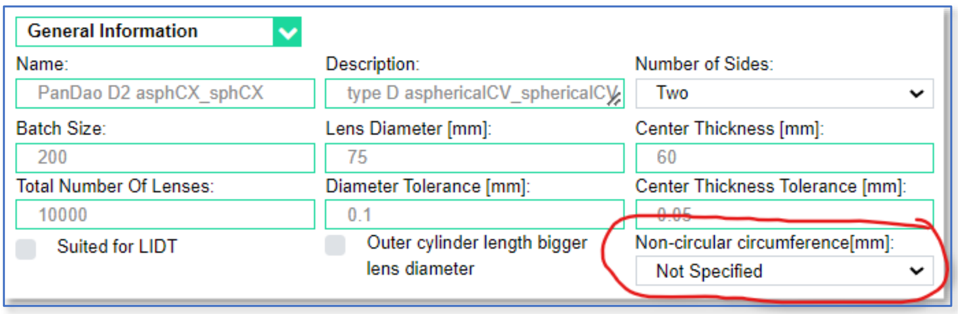
PanDao models the center grinding process and identifies out of many different centering technologies (such as bell chucking, pre-mounted SPDT, fluid jet grinding, transfer mandrel grinding, etc.) the optimum one for your optical element.

The optimum center grinding technique is being displaid in the output data generated by PanDao.

2.2. CYLINDRICAL SURFACES

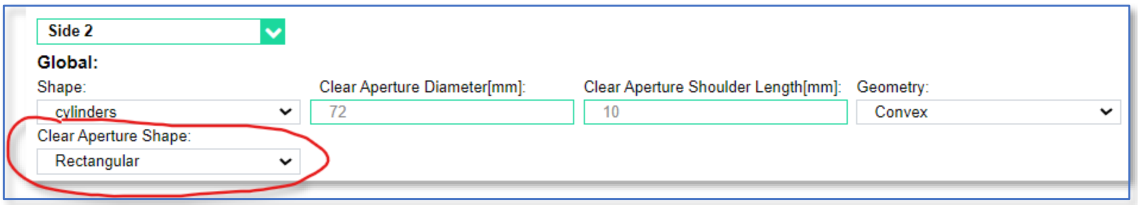
What is the current PanDao status on cylindrical surfaces?

PanDao covers the generation cylindrical surfaces for which numerous optical fabrication technioliogies are existing.
As standard, PanDao reads in circular optical elements featuring a lens diameter (to be inputted in the general input section) . For other outer diameter shapes than a circle, e.g. a rectangle, please use the PanDao feature “non-circular circumference”



as described in chapter ***2.1 “what are non-circular perimeters?***

There are two cockpit for the shape of the clear aperture: circular and rectangular which can be selected in the scroll down menue:



A-circular surface shapes (e.g. for fast axis collimation FAC optics) are not yet covered by PanDao (see development stage in chapter5).

2.3. ASPHERICAL SURFACES

What is the current status of PanDao on aspherical surfaces?

Aspherical surfaces are rotary symmetric surfaces with a non-circular cross-section which are usually described by a power series description as follows:

$$z = \frac{y^2}{R(1+\sqrt{1-(1+K)y^2/R^2})} + Ay^4 + By^6 + Cy^8 + Dy^{10} + Ey^{12} + Fy^{14}$$

As input, PanDao does not require the absolute shape description, but rather parameters derived from it that are relevant for setting up optical manufacturing processes along the manufacturing chain, e.g. smallest radius of curvature, asphericity etc. These parameters can be determined by using PanDao's PRO-OPTIC CONVERTER (see chapter 2.1 "*PRO-OPTIC-CONVERTER: How can I determine and convert lens tolerances so that PanDao can reads them?*").

The conversion from power series description to Greg Forbes polynomials is currently under development and will be added to the PRO-OPTIC CONVERTER soon.

What is the "removal sphere" for a given aspherical, off-axis aspherical or freeform surface?

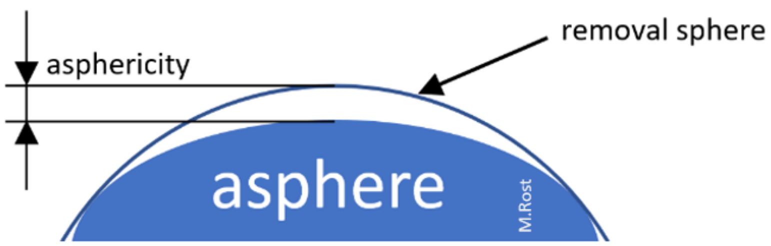
The removal sphere is the enveloping spherical surface that is located outside of the material not intersecting with the surface to be generated; it is located as close as possible above the surface to be generated without intersecting.

You can find this parameter in the output data generated by the optical design software.

What should I enter, if (e.g. for freeform surfaces) no "removal sphere" is known?

Please enter earth radius 6400'000'000 mm = 6400 km

What is "asphericity"?



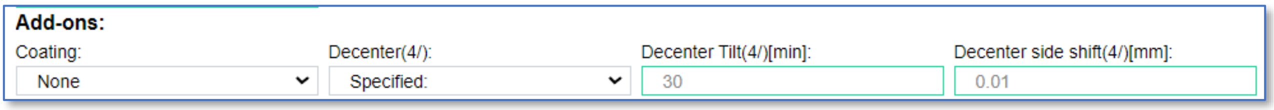
In contrary to optics design, PanDao defines asphericity as the maximum vertical distance from the “removal sphere” to the aspherical, off-axis aspherical or freeform surface.

You can find this parameter in the output data generated by the optical design software.

How do I define the centering tolerance for an aspherical surface?

Aspherical shapes have no point symmetry. Therefore, tilting and side shifting result in different decenter effects and have to be defined separately.

Consequently, for aspherical surfaces, ISO 10110 uses e.g., the following notation **4/x (y)** with “**x**” describing the lens tilt in minutes and “**y**” being the maximum allowed lens side shift in mm:



What is aspheres generation by asphérisation?

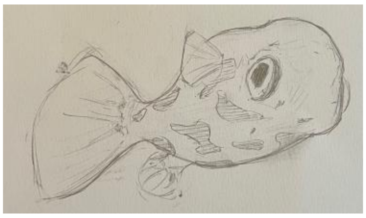
Traditionally, aspherical surfaces are being cnc point-contact ground and subsequently sub-aperture ccp-polished (ccp: computer controlled polishing). At certain tolerance and characteristic parameters combinations, e.g. for small asphericities (the distance to the best fit enveloping spherical surface), it is advantageous to generate the enveloping best fit spherical surface first and subsequently using the ccp method only for final aspherisation

You can find all the details and an exanple in the following paper:

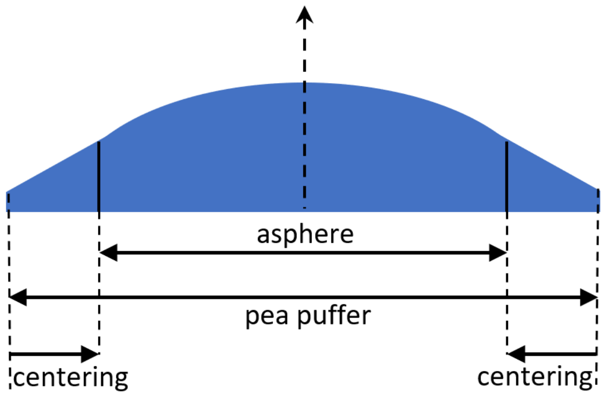
- O.Faehnle, J.DeGrote Nelson et.al. “The pea puffer aspheres: circumference optimized aspheres ccp polishing”, EOSAM24 conference on “Optical system design, tolerancing and fabrication“, European Optical Society (EOS), Napels, Italy, September 2024.

What is pea puffer asphere polishing?

First published by PanDao GmbH in 2024 at the “optical design, tolerancing and fabrication conference” of the Eurepean Optical Society (EOS) in Naples, Pea Puffer asphere polishing is a fabrication method for aspheres with small clear apertures.



Pea puffer is applied in certain situations, e.g. if an asphere is unsuited for certain ccp finishing methods [O.Faehnle, OFT&T conference, Monterey, 2012]. In this case, PanDao adds pea puffer polishing to the 360 standard OFTTs (Optical Fabrication Technology Techniques).



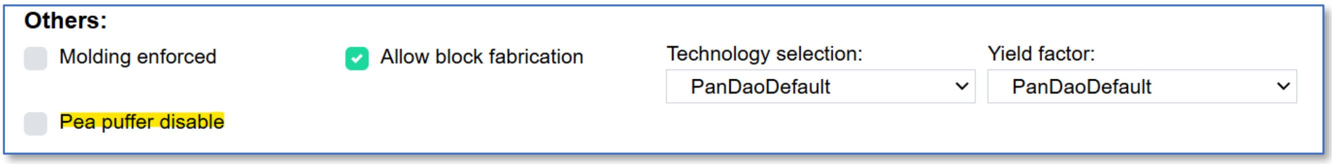
For the asphere to be generated, a bigger pea puffer lens is fabricated enabling a bigger spectrum of applicable OFTTs. Subsequently the pea puffer lens is centered down to the originally required diameter of the asphere.

In some circumstances this

- enables the manufacture of some aspheres which would normally not be possible,
- enables cost reductions because cheaper OFTTs can be applied.

The PanDao tool will tell you if the pea puffer asphere fabrication method has been applied.

In the cockpit, you can also disable the usages of pea puffer for comparison:



You can find all the details about Pea Puffer in the following paper:

- O.Faehnle, J.DeGrote Nelson et.al. "The pea puffer aspheres: circumference optimized aspheres ccp polishing", EOSAM24 conference on "Optical system design, tolerancing and fabrication", European Optical Society (EOS), Napels, Italy, September 2024.

2.4. OFF-AXIS ASPHERICAL SURFACES

Off-axis aspheres: what is “offsetR”?

“offsetR” is the lateral distance from the symmetry axis of the asphere to the center of the clear aperture of the off-axis asphere.

Off-axis asphere: what should I enter at Center Thickness?

Please consult the stereotype lens drawings: Please enter the local minimum lens thickness called “gauge”.

Off-axis aspheres: what should I enter at “smallest radius of curvature” and at “smallest concave radius of curvature (SCRC)”?

Please consult the stereotype lens drawings: Please enter the smallest radii of curvature of the whole aspherical surface out of which the off-axis asphere is being generated with production diameter = 2 * (minRClearAberture + lens diameter).

Off-axis aspheres: How do I enter the 4/ centering accuracy?

There is currently no 4/ specified: Please enter 4/ at the other side of the lens, only. Currently, no center grinding cost for freeforms are generated.

Please note that cost for setting *fiducials* needed for matching the coordinate systems of (a) the machine and (b) the testing device and (c) the mounting setup are not taken into account, currently.

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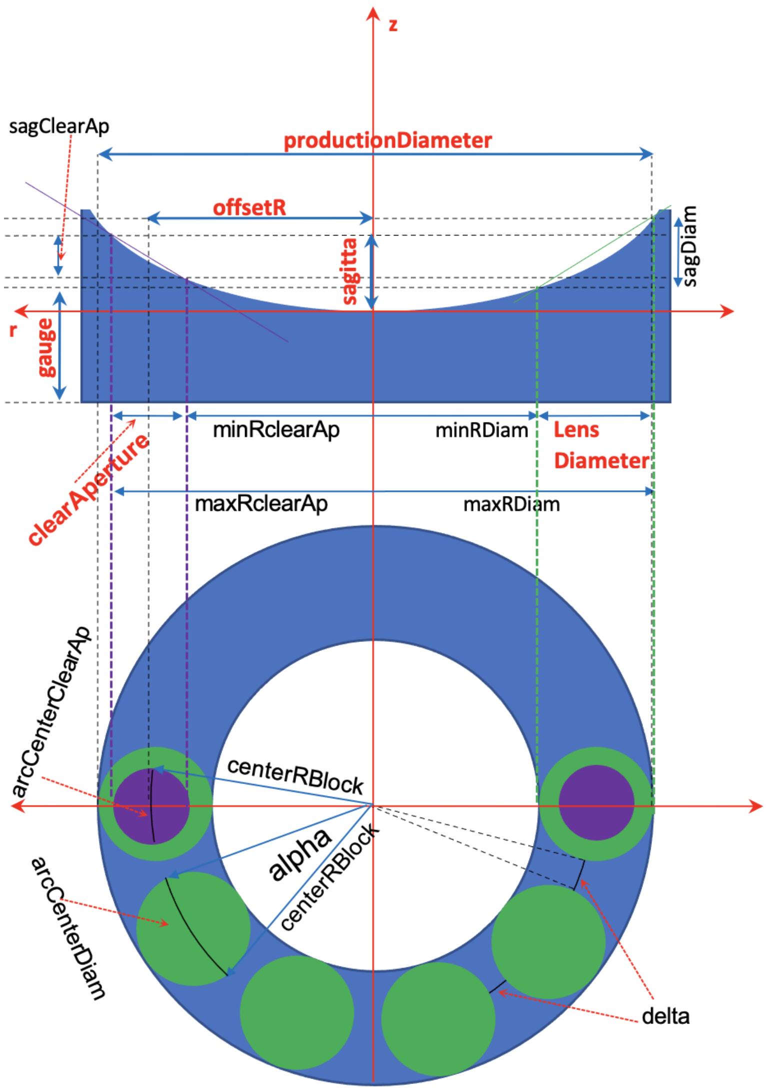
PANDAO FROM OPTICS TO FABRICATION

Off-axis aspheres definitions



LEFT SIDE (side 1)

clearAperture Φe: circle
prot.chamfer (length): -
coating (AR/special):
3/power(irregularity)
~~4/centering asccuracy~~, not applicable*: see FAQ*
5/
6/ (if > 10J/cm^2 = LIDT)
Sq surface roughness
smallest midSpatialWaelength:
sagitta

off-axis asphere:

smallest radius of curvature
(of the whole asphere within
production diameter)
asphericity
radius removal sphere:
contains concave parts (YES/NO)?
SCRC
(smallest concave radius of curvature
of the whole asphere within production diameter)
offsetR
sagDiam
sagClearApp

MATERIAL:

if glass (YES/NO):
HK:
AR:

DIMENSIONS

"center thickness"**ct** = **gauge**
(for of-axis aspheres and freeforms: enter local minimum lens thickness = gauge as center thickness)
ct tolerance
lens diameter
production diameter
(= 2*(minRdiam + 2*lensDiameter))
diam tolerance

PRODUCTION ORDER

totalNumber pcs
batchSize pcs:
TRL level
yield

RIGHT SIDE (side 2):
currently flats only !

2.5. FREEFORMS

What should I enter at Center Thickness?

Please consult the stereotype lens drawings: Please enter the local minimum lens thickness called “gauge” located under the maximum sagitta (sag) of the freeform.

What is the definition of the parameter “MLC of SCRC”?

The “MLC of SCRC” is the Maximum Local Cross section (MLC) of the area with the Smallest Concave Radius of Curvature (SCRC). Please consult the freeform stereotype drawing.

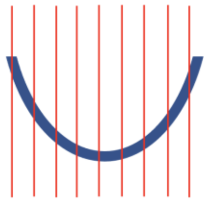
Do freeform surfaces have any symmetry?

No. Freeforms do not have any kind of symmetry and are defined by a data cloud: z(x,y).

What should I enter at “MLC of SCRC” (Maximum Local Cross section (MLC) of the area with the Smallest Concave Radius of Curvature (SCRC))?

Please consult the stereotype lens drawings:

a) if MLC is known, please enter MLC of SCRC in mm;
b) if local radii are continuously varying along the clear aperture (dR/(dx, dy) ≠ 0) then Please enter 0.01 mm (which is a typical incremental distance between data points used in CNC programming).



How do I enter the 4/ centering accuracy for freeform optics?

There is currently no 4/ specified: Please enter 4/ at the other side of the lens, only. Currently, no center grinding cost for freeforms are generated.

Please note that cost for setting *fiducials* needed for matching the coordinate systems of (a) the machine and (b) the testing device and (c) the mounting setup are not taken into account, currently.

What is the definition of the parameter “localSag at SCRC”?

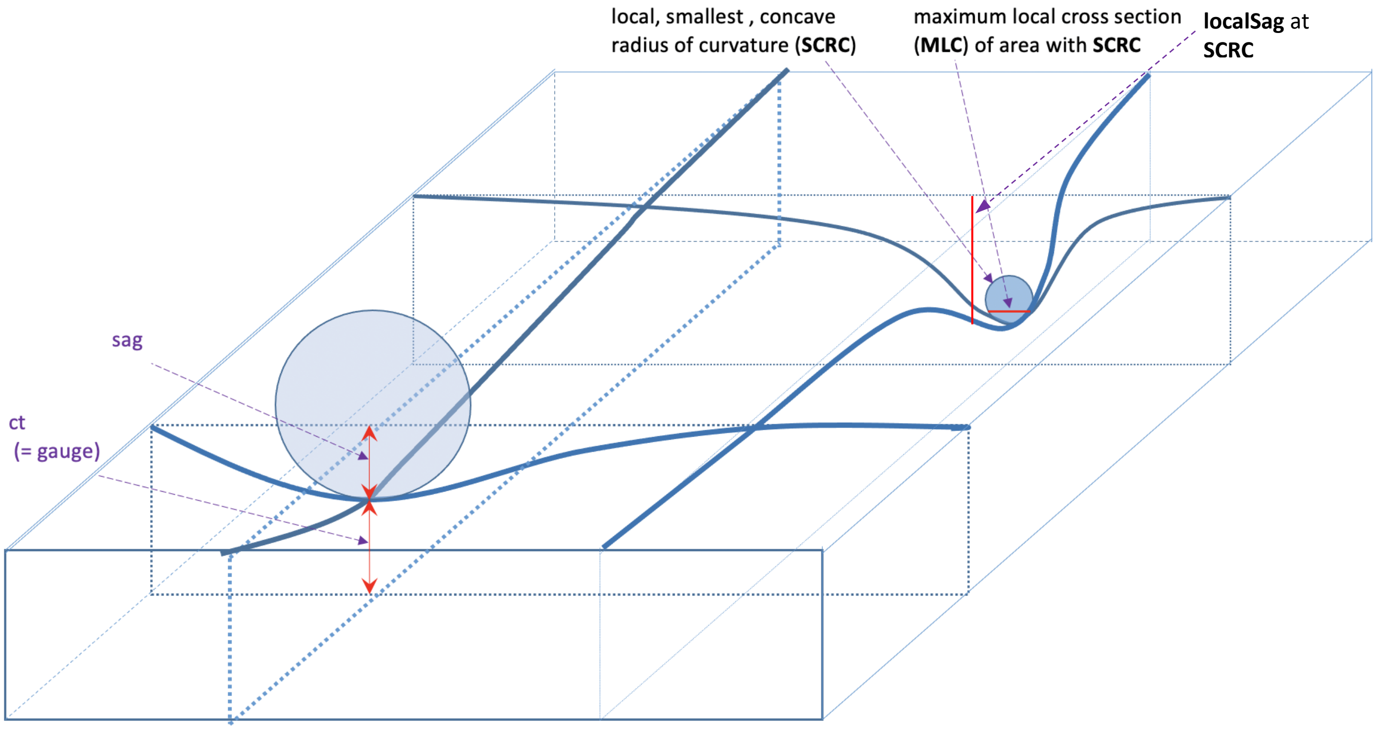
The “localSag at SCRC” is the local sagitta at the point z(x,y) where the smallest concave radius of curvature (SCRC**)** is located. Please consult the freeform stereotype drawing.

Why is PanDao not informing about centering of freeform optics?

There is currently no industry standard for free-form centering; it is done, for example, by fiducials, extended ring assembly, or optically or by wafer stack technologies.

PanDao advises on request within the DesignToFabrication service

Freeforms definitions



LEFT SIDE (side 1)

clearAperture Φe: circle
prot.chamfer (length):
coating (AR/special):
3/power(irregularity)
~~4/centering asccuracy~~, not applicable*: see FAQ*
5/
6/ (if > 10J/cm^2 = LIDT)
Sq surface roughness
smallest midSpatialWaelength:
sag

if freeform (YES/NO):

smallest radius of curvature
asphericity: ***see FAQ***
radius of removal sphere: ***see FAQ***
contains concave parts (YES/NO)?
smallest concave radius of curvature (**SCRC**)
MLC of **SCRC**
(Maximum Local Cross section (MLC) of the area with the Smallest Concave Radius of Curvature (SCRC))
localSag at **SCRC**
(local sagitta at the point z(x,y) where **SCRC** is located

MATERIAL:

if glass (YES/NO):
HK:
AR:
Alpha:

DIMENSIONS

"center thickness"**ct** = **gauge**
(for of-axis aspheres and freeforms: enter local minimum lens thickness = gauge as center thickness)
ct tolerance
lens diameter
diam tolerance

PRODUCTION ORDER

totalNumber pcs
batchSize pcs:
TRL level
yield

RIGHT SIDE (side 2):
any shape allowed

2.6. Prisms

Prisms?!

Prisms enable us to look around the corner and to split white light into its colors. This trick is well known in nature with examples like

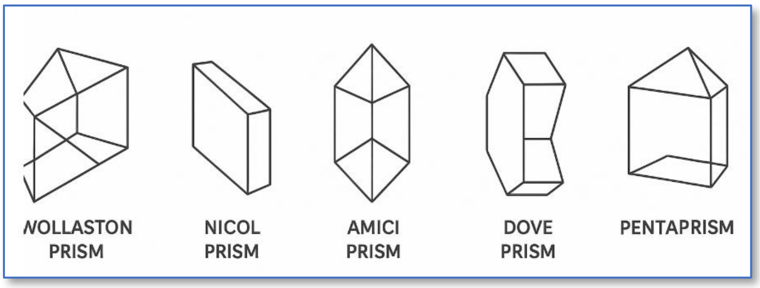
- ice crystals in the atmosphere: hexagonal ice prisms in cirrus clouds cause halos, sun dogs, and other colored arcs;
- quartz, diamond, and other transparent crystals: naturally form prism-shaped crystals that can refract light, sometimes splitting white light into rainbow fringes.

Prisms have been known for quite some time and have been mentioned by a.o. Seneca (1st century AD) and Newton (Opticks 1704).

Examples of today's prism applications include endoscopes, periscopes, entrance optics for satellite systems, as well as micro-optics projectors for XR and LIDAR systems for e.g.self-driving cars.

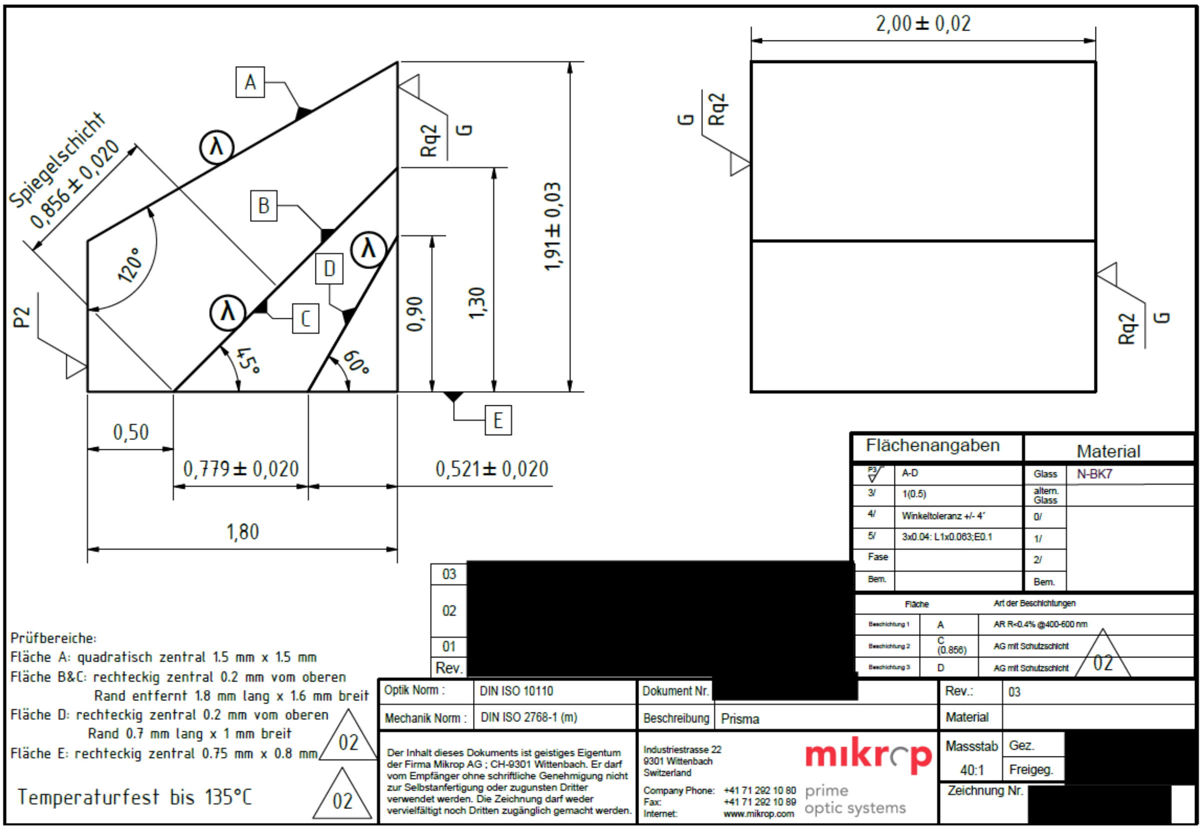
From a ray tracing point of view, prisms reflect and transmit incident light rays, causing various internal (or total-internal) reflections before the light is transmitted in a specific, precisely defined new direction, which may differ from the incident direction.

Among many, here some famous prisms for specific light tasks:

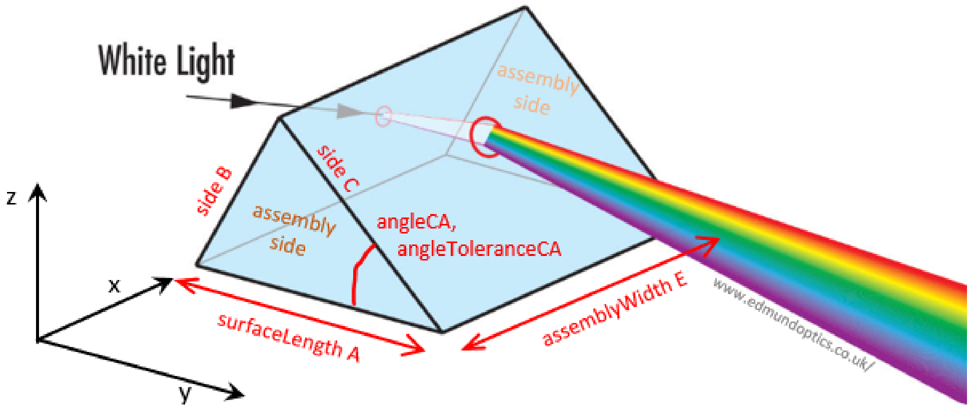


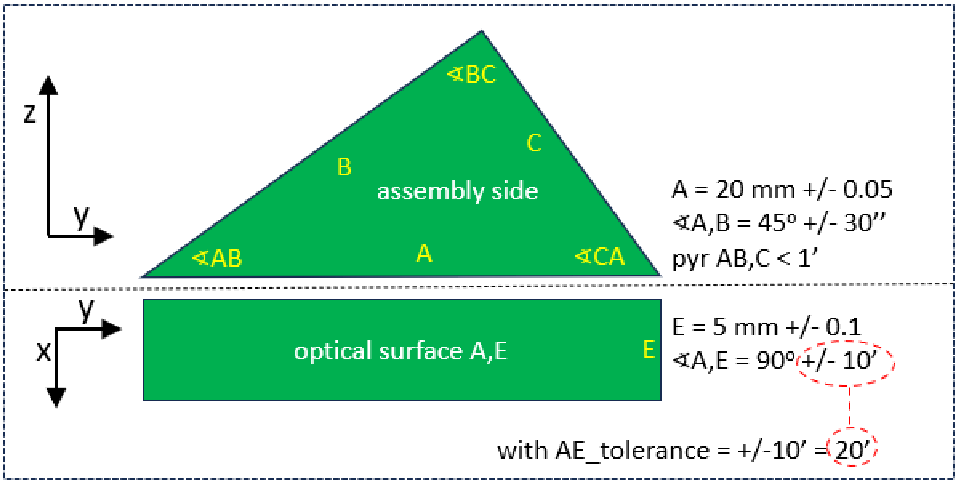
- ***Wollaston*** prism (William Hyde Wollaston, England, 1820): A birefringent prism that splits light into two beams of orthogonal polarization which is needed e.g. for Nomarski microscopy,
- ***Nicol*** prism (William Nicol, Scotland, 1828): One of the earliest polarizing prisms, transmitting only a single polarization,
- ***Amici*** prism (Giovanni Battista Amici, Italy, 1860): A dispersive prism that can deviate and invert a spectrum without inverting the image,
- ***Dove*** prism (Heinrich Wilhelm Dove, Germany, 1938): Inverts an image and can rotate it as the prism is rotated, and
- ***Penta*** prism (Industrial adoption by Leica/Contax, Germany, 1935): Deflects light by 90° while keeping the image orientation.

In optics technologies and industry, prisms are described for manufacture by technical drawings and defined in accordance with e.g. the ISO10110 (or MIL) standard.



High-end industrial micro prism with many thx to https://mikrop.com.





Prisms usually have different accuracy and precision requirements along the x- and y- axes. This is because the z,y plane, which forms the prism's cross section, defines its ray tracing quality. In contrast, the tolerances along the shoulder in the x direction, which are determined by

(1) the rectangularity of the shoulder to the two assembly surfaces forming the cross section and
(2) the prism's pyramidal errors,

mainly influence image quality and the main direction of light propagation in the optical system the prism belongs to. So in general, prism tolerancing in the z,y plane is tighter than it is along the x-axis.

The cross-section of a prism in the z,y plane is responsible for ray tracing light (for e.g. a triangular prism with sides A, B and C in the z,y plane). The triangular prism's three clear apertures are located on the surfaces AE, BE and CE. The distance E equals the shoulder length along the x axis of the prism and is called assembyWidth. The two side surfaces of the prism (separated by the assemblyWidth E) are called assemblySides. The rectangularity of the assemblySide to the optical surfaces AE, BE and CE is called AE_tolerance and given in [minutes].

Since the **pyramidal error** often causes discussions in workshops, we want to have a closer look at it. The pyramidal error, written as pyrAB,C < 10′, is defined as the angular deviation of surface CE from its nominal orientation, after surfaces AE and BE have been aligned such that their line of intersection defines the x-axis. The pyramidal error is always given for one side with respect to two other sides of the prism. Consequently, we can state that pyr is a measure for the inclination the three sides of the traingle prism on their way to the tip of a pyramid, in case they would form one.

To understand the origin of the word pyramidal error, lets visit the Cheops pyramid in Egypt.

If we have a look at the Cheops pyramid and assume that Cheops should be a quader with four vertical sides: Now, as we see in the picture there is an angular inclination of cheop's four sides with respect to each other: each surface has a pyramidal error of pyr = 38∘9′36″ which causes that all four surfaces meet in one point in space, at the tip of cheops in 146.6 m height above its center. Therefore, Cheops is a pyramid.

For prisms, the pyramidal errors can be different values for each side. This means that in optics, not necessarily pyramides are generated if a prism features a pyramidal error.

For further reading about the pyraminad tolerancing and measurement of it, please refer to:

- Jaramillo-Nunez, Alberto, and Carlos I. Robledo-Sanchez. "Measuring the angles and pyramidal error of high-precision prisms." Optical engineering 36.10 (1997): 2868-2871.

How do I enter prism data into PanDao?

PanDao handles prisms according to ISO10110. Currently, the following types of prisms are supported:

Number of optical surfaces	Name of prism	Comment	Shape of cross section
2	**Wedge plates**	Two optical surafces not parallel to each other. Please consult the chapter 4, “master class”. The sum of all angles is 360º.	
			
3	**Triangular prism**	Different types of prisms featuring three optical surfaces and two assemblySides. The sum of all angles is 180º.	
			
4	**Quadrilateral prisms**	Different types of prisms featuring four optical surfaces and two assemblySides. The sum of all angles is 360º.	
	cube	square cross-section	
	quader	Rectangular cross-section	
	trapezoid	Trapezoidal cross-section with max. two sides parallel	
	parallelepiped	Cross-section is a paralellogram without any 90 degrees angles	
5	**Penta prisms**	Different types of prisms featuring five optical surfaces and two assemblySides. The sum of all angles is 540º.	
		Kite or any other shape	

Pandao supports prism analyses under the following boundary conditions: Please enter your prisms by using the following parameters below.

In the **General Information section**

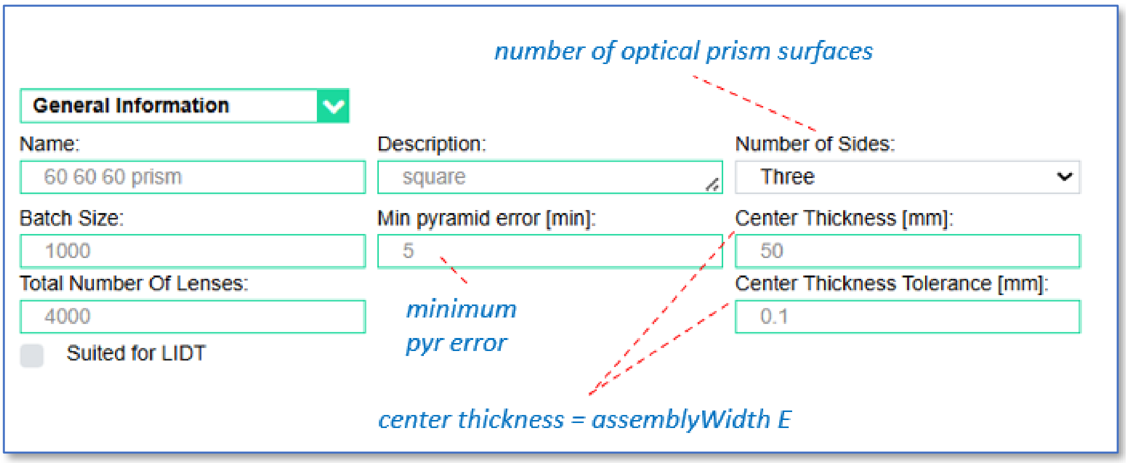
Prism's projection into the x,y plane is a rectangle; their cross-section in the z,x plane is used for ray tracing light and called assemblySide. All prism's surfaces are flat.

All PanDao features and cockpit parameters apply also to prisms, with the exception of the parameter for centering accuracy (4/), which does not apply.

Prisms are generated in prism strips and separated by the best out of several optical splitting technologies such as laser cutting, water cutting, wheel sawing, endless wire sawing or waver sawing, etc.

Prisms are treated as flat surfaces by default, but have more than two surfaces: in the 'General Information' section, select the number of optical surfaces you want the prism to have: either 3, 4 or 5 sides:

- Side1, side2, side3, side4 and side5



The minimum pyramidal error needs to be specified:

- Min pyramid error = 2'

The 'Center Thickness' parameter in the 'General Information' section defines the assemblyWidth E of the prism shoulder and its tolerance.

Prisms feature two assemblySides located left and right of the prisms shoulder length and both have the same surface quality.

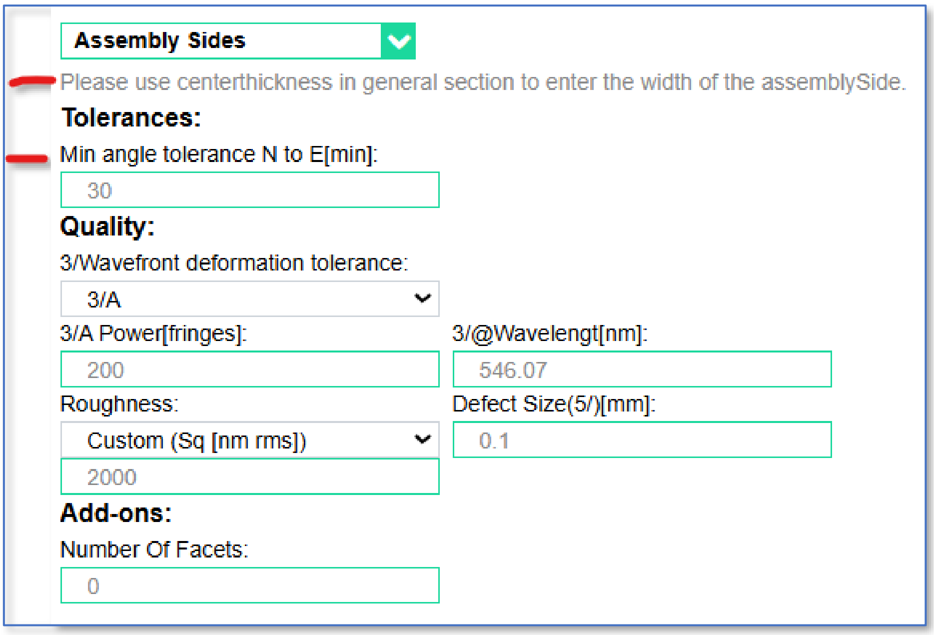
In the **AssemblySides section**

Prisms feature two assemblySides located paralellel to the z,y plane and perpendicular to the surfaces AE, BE and CE:

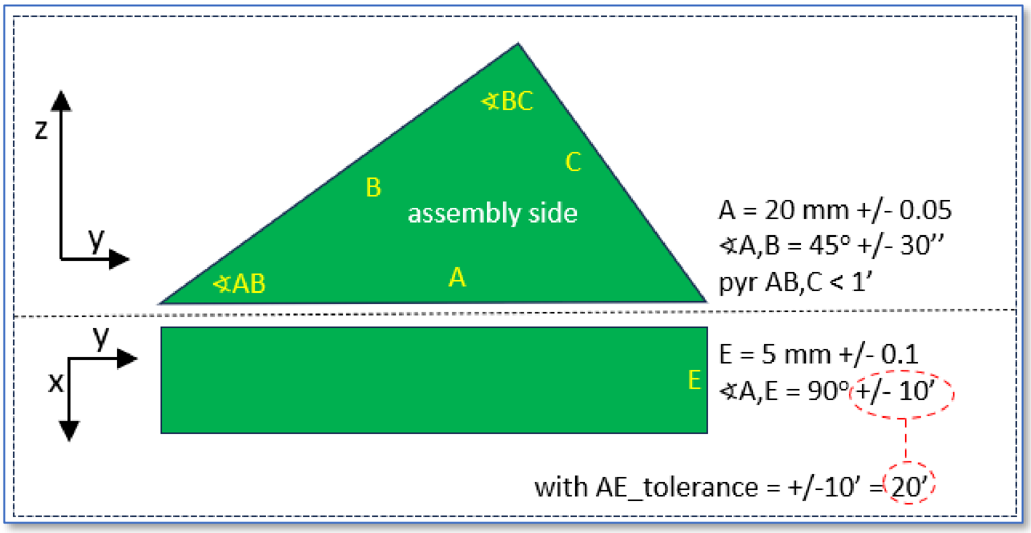
- ∢A,E = ∢B,E = ∢C,E = 90°

The assembly sides are separated by the assemblyWidth E (along the x-axis).

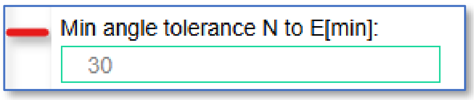
Both assemplySides feature the same surface quality and no clear aperture.



Input the assemblyWidth E in the 'General Information' section as the prism's 'Center Thickness ' and 'Center Thickness Tolerance'.



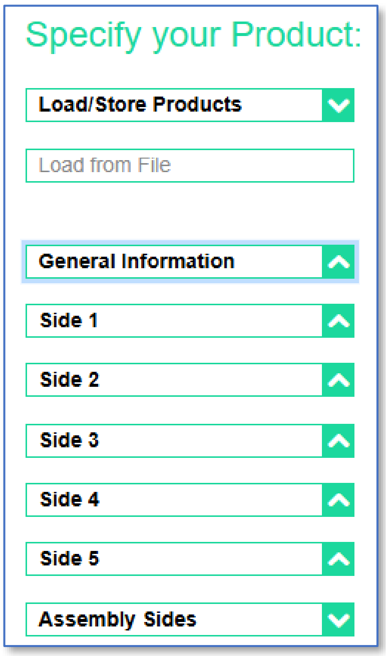
Input the minimum of the 90° angular tolerances of the optical surfaces to the assemblySides (e.g. AE_tolerance = 20'):

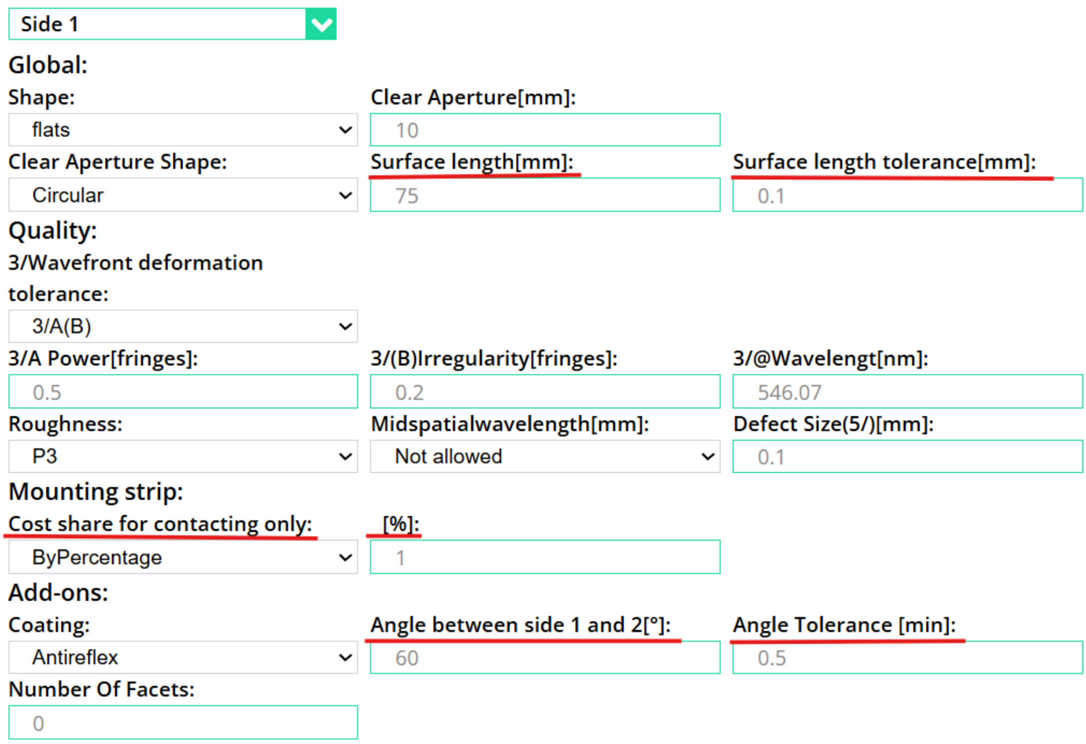


- 'Min angle tolerance N to E' = Min(AE_tolerance, BE_tolerance and CE_tolerance)

<u>In the **SideN section** (the individual optical surfaces AE, BE, CE, or side1, side2, side3, etc)</u>

After having chosen in the 'General Information' section the number of surfaces of your prism, each of them has to be filled out individually:





Input parameter are the length of this side, its tolerance, as well as the angle between this side and the next one and its tolerance.

Please note that according to ISO10110 and PanDao we are counting prism sides (in the z,y plane cross-section) clockwise around the prism: Starting at any of its surfaces. The selection of the first surface to be generated (=side1) is important, as its manufacture does not require any mounting strip or optical contacting (as its "back side" simply does not yet exist):

- So please choose side1 wisely!

Prism sizes are currently limited to:

0.75 mm < surfaceLength_sideA < 120 mm

1 mm < assemblyLength_E < 80 mm

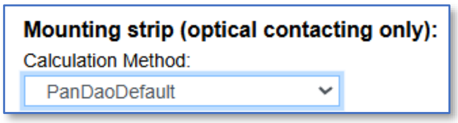
For the case that optical contacting is needed to manufacture your prism, you have to specify how much of the mountingStrips (on which the prism strip is being optically contacted) cost you want to be shared with your customer (percentage or absolute cost). Usually, companies are not charging their customers for mountingStrip cost – with the exception of non-standard angles within the prism.

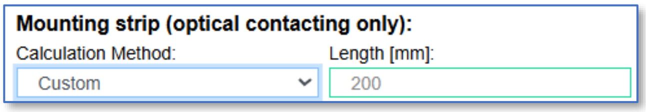
PanDao's default value is 0.01%.

- 'Cost sharing for contacting only' = 0.01%

<u>In the **Cockpit section**</u>

Per default, the (optical contacting) mounting strip length, width, angle and tolerances are determined by PanDao. Nevertheless, you can overrule the mounting strip length (maximum mountingStripLength currently yields 250 mm).





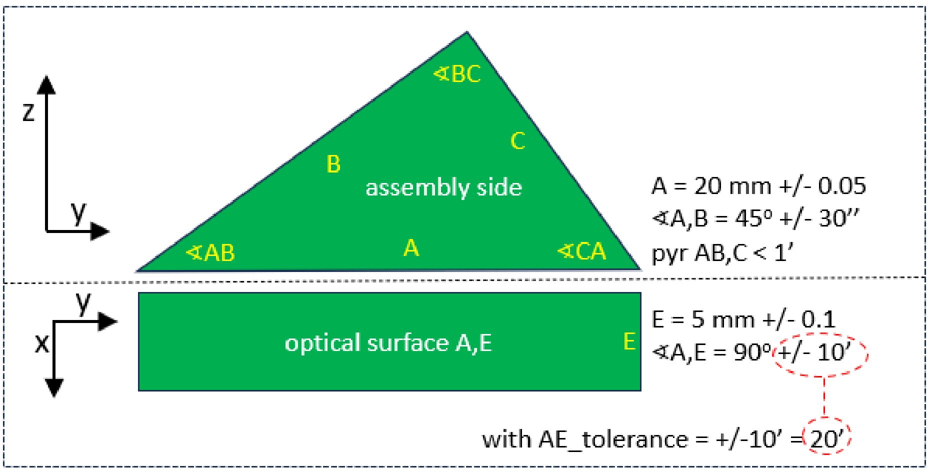
Two options for setting up the length of the mounting strip: It is either being determined by PanDao or overruled by you.

The mounting strip length depends on the set of sides N,E_tolerances, the spectrum of pyramidal prism errors, its width-length-thickness-angle ratio, the mountingplate diameter and the layout strategy of the block fabrication set-up

Please note that mounting strip angle, width, thickness and tolerancing is determined by PanDao.

Summary: entering prism data into PanDao

Triangular Prism (ISO10110)



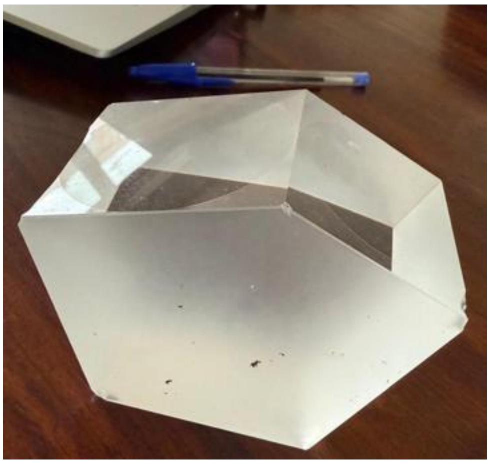
Technical Drawing	**PanDao**

prism parameters	examples	input section	input field
surface length of an optical surface in the z,y-plane	A = 20 [mm]	Side 1	Surface length[mm]: 45.28
surface length tolerance	A = +/- 0.05 [mm]		Surface length tolerance[mm]: 0.1
angle between two optical surfaces	∢A,B = 45° [degrees]		Angle between side 1 and 2[°]: 135
angular tolerance between two optical surfaces	∢A,B = +/- 30'' [minutes]		Angle Tolerance [min]: 0.5
mounting strip for optical contacting	customer pays 1% of the mounting strip		cost sharing of optical contacting mounts [absolute or %] **Mounting strip:** Cost share for contacting only: ByPercentage [%]: 1
	mounting strip length	Cockpit	is determined by PanDao "per default". **Mounting strip (optical contacting only):** Calculation Method: PanDaoDefault User can overrule. **Mounting strip (optical contacting only):** Calculation Method: Length [mm]: Custom 200
	mounting strip width and thickness and tolerancing is determined by PanDao		
width of the prisms: the shoulder length along the x-axis	E = 5 [mm]	General Information	Please use centerthickness in general section to enter the width of the assemblySide. Center Thickness [mm]: 30
shoulder length tolerance	Ë = +/- 0.1 [mm]		Center Thickness Tolerance [mm]: 0.1
angle between assembly side and an optical surface	∢A,E = 90° [degrees]	Assembly Sides	PanDao handles currently 90 degrees per default.
angular tolerance assembly side and an optical surface: the AE_tolerance	∢A,E = +/- 30'' [minutes]		minimum of all AE_tolerances required: Min angle tolerance N to E[min]: 5
pyramidal error on one surface with respect to two others	pyr AB,C < 1' [minutes]		minimum of all pyramidal errors required:

			Min pyramid error [min]: 5

Prisms manufacture ?!

The manufacture of a prism is the generation of flat optical surfaces (facets) precisely positioned and oriented relative to each other within a workpiece.



Penta prism featuring five optical flat surfaces.

In general, there are four different approaches to manufacture a prism made of mineral or organic glass:

(1) ***(1) Draw Towering,*** drawing prisms from a master produced on an ultra-precision circumference grinding and polishing machine (UPM). The master is mounted on a glass drawing tower, where its cross-section is reduced by controlled heating and drawing to achieve the desired prism dimensions. Afterward, the assembly width (shoulder) of the prisms is formed through mass-production cutting. This is by far the most cost-effective mass-manufacturing process for prisms. The main challenges lie in controlling birefringence and compensating for shape deviations during master fabrication, which result from surface sag in the drawing process, as well as from limitations in achievable dimensions and the inability to produce anything other than mass-production quantities. Draw towering also enables the production of aspherical micro-prisms, for example fast-axis collimation (FAC) optics in very high quantities.
   - James J. Snyder, Patrick Reichert, and Thomas M. Baer, "Fast diffraction-limited cylindrical microlenses," Appl. Opt. 30, 2743-2747, 1991
   - T. Seto, K. Saito, and S. Nakajima, "High-precision prism production using drawing method", Electronics Letters Journal, Volume 40, Issue 11, 2004

(2) ***Molding*** by either precision glass molding (PGM) or injection molding. The main challenges in these processes include (a) birefringence caused by temperature gradients and glass flow effects during pressing and cooling, (b) the accuracy of shape transfer from the steel or tungsten carbide (WC) mold into the glass, and (c) managing prism volume overflow at the mold edges, which often requires costly corrective removal, for example by CNC grinding.

(3) ***3D printing*** which is currently not yet in an acceptable accuracy range to be applicable for prisms generation

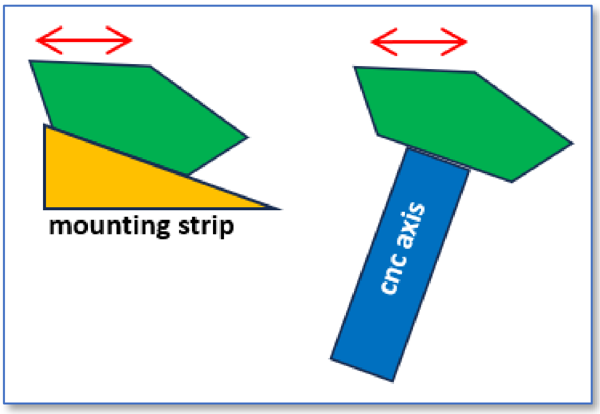
(4) ***Abrasive machining*** applying the optimum optical fabrication technologies out of the 350 different ones existing.

Offering the highest optical quality as well as flexibility in prism dimensions, achievable accuracy, and production scalability, ***abrasive machining*** remains still today the state of the art in prism manufacturing within the optics industry.

Abrasive machining

Prisms generation by (abrasive) machining is a sequential series of flat optical surface generations while positioning the workpiece for each surface in a precise 3D orientation to ensure the final prism geometry.

To minimize the complexity and effort of positioning any tool within the plane of the prism's flat surface to be generated, this surface is typically oriented horizontally in the optical fabrication machine (e.g. a CNC, overarm, ion-beam, or MRF polisher). The horizontal orientation keeps the setup simple for both machining and tool alignment, thereby enabling maximum precision and accuracy with minimal effort. This positioning can be cariied out by a workpiece axis positioned in 3D or by applying a mounting strip applying the "counter angle" of this flat side of the prism with respect to all other prisms sides.

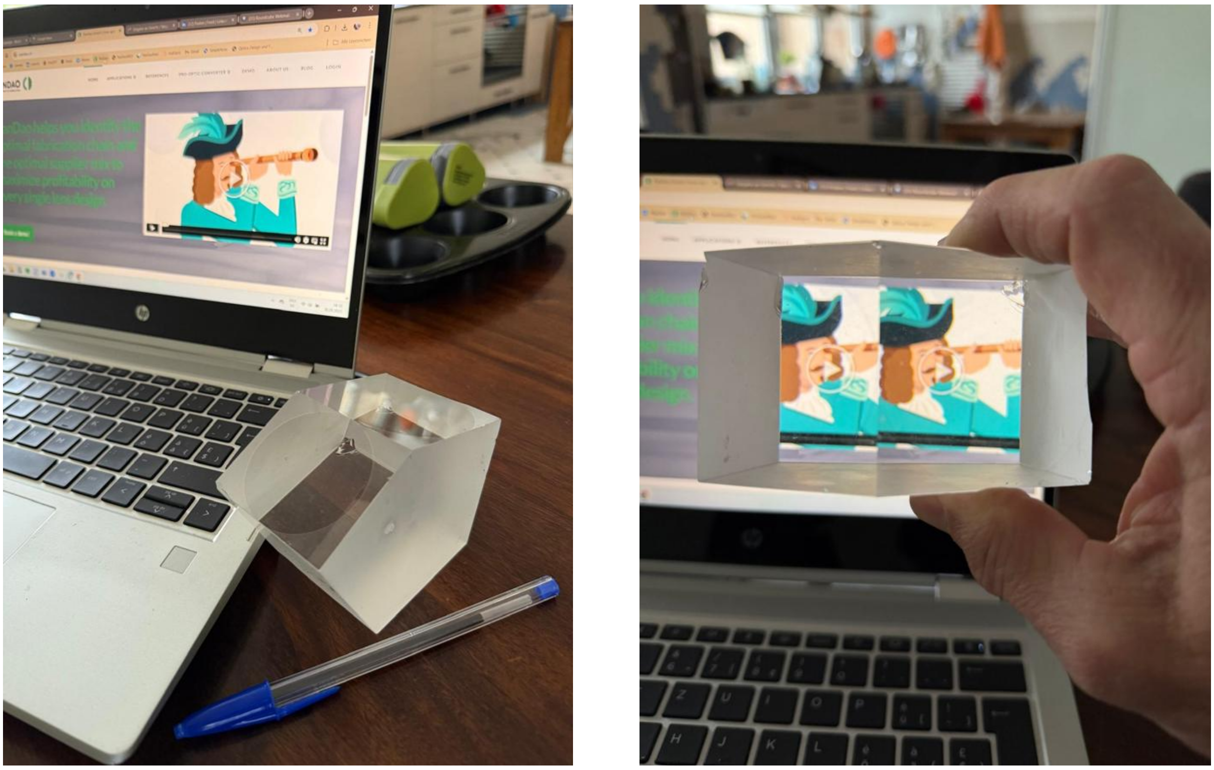


Positioning one of the flat surfaces of a penta prism horizontically for manufacture: either by applying a mounting strip and optical contacting or by mechanical mounting e.g onto a cnc machine axis.

How is PanDao handling prisms manufacture?

Currently, PanDao excludes prisms generation by draw towering (due to shape accuracy and birefringens issues) as well as by molding (volume overflow and birefringence issues) and 3D printing (material homogeneity and angular accuracy issues); PanDao focuses on abrasive machining of prisms.

PanDao allows about 350 optical fabrication technologies (OFTs) to compete with each other to generate the optimum fabrication chain for a given prism, if they are suitable.



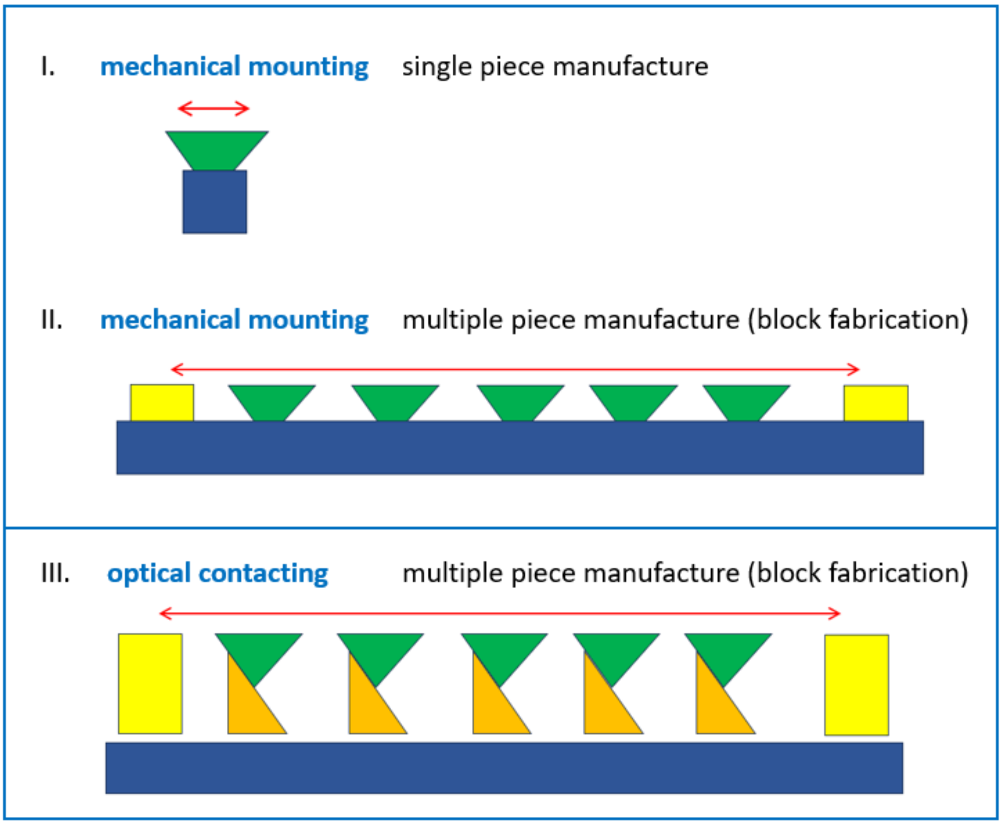
Panta prism to be analysed by PanDao

PanDao uses the prism's tolerances, geometry, and dimensions to determine the required level of precision and corresponding manufacturing tasks.

Two distinct regimes are applicable in prism manufacture differing by their mounting approaches employed (see also chapter2.1 “…different ways to mount optical elements for manufacture”):

(1) either **mechanical mounting** (eleven different types of fixing the workpiece onto the mount)

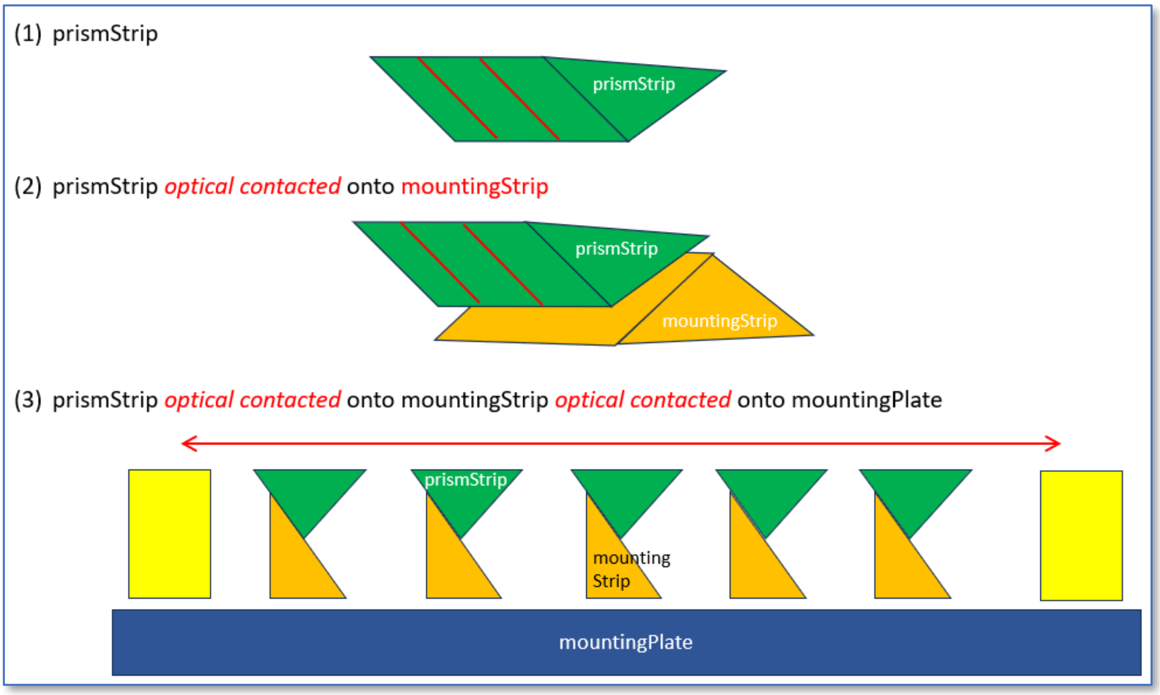
(2) or **optical contacting** (fixing the workpiece by van der Waals forces onto the mount).



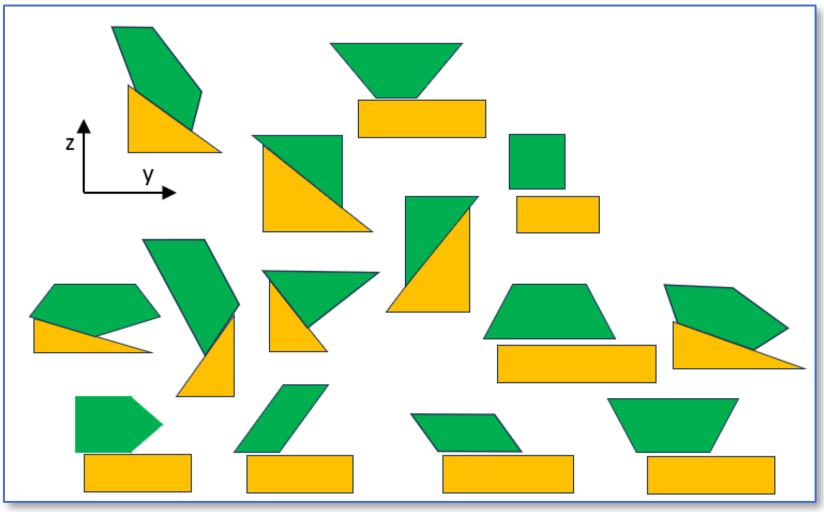
MOUNTING PRISMS	mechanical mounting	optical contacting
single piece manufacture applicable?	yes	no
block fabrication applicable?	yes	yes
accuracy of prism generated	medium to high	high to outermost
mount material	any	fused silica, glass, glass-ceramics (like Zerodur)
workpiece holding force	fixation, clamping, adhesive etc	van der Waals
special requirements?		up-side of the mounting strip as well as the back-side of the prism that contact each other must be polished

In prism manufacturing, ***mechanical mounting*** offers lower accuracy but supports a wider range of optical fabrication techniques (OFT). It also allows both single-piece fabrication and multi-piece block fabrication

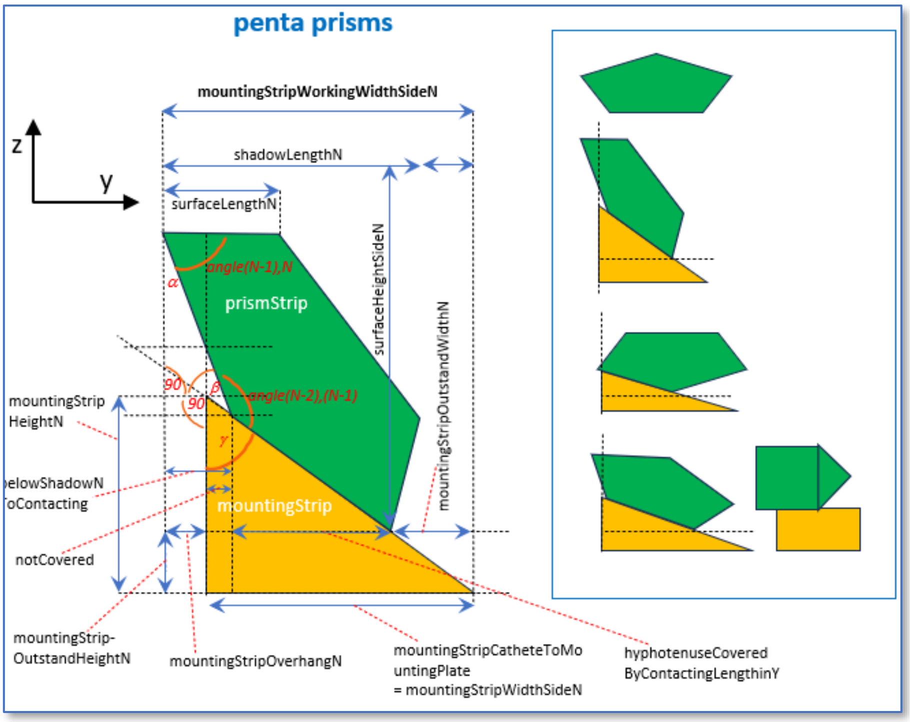
In contrary, ***optical contacting*** is used to achieve the outermost prisms angular and shape accuracies. Optical contacting in prisms manufacture is only applied in a multiple prisms holder set up applying block fabrication (see chapter 2.1 "…block fabrication.."); it is not used for single prism fabrication.



The high accuracy and quality of prisms manufactured in the optical contacting regime result from the perfect mounting precision achieved through optical contacting using van der Waals forces (see Chapter 2.1, "…different Ways to Mount Optical Elements for Manufacture…"). In this process, the prism strip is optically contacted to a glass mounting strip ("Ansprengstreifen") featuring high-quality polished surfaces and the angular accuracies required for the final prism. Mounting strips cross-sections are usually either right-angled triangles or rectangles. Because the van der Waals bond forms without any intermediate layer (such as cement) the angular accuracy of the mounting strip is transferred to the prism strip without loss of precision. The combined element, consisting of the prism strip and the mounting strip, is then optically contacted to a mounting plate to enable block fabrication.

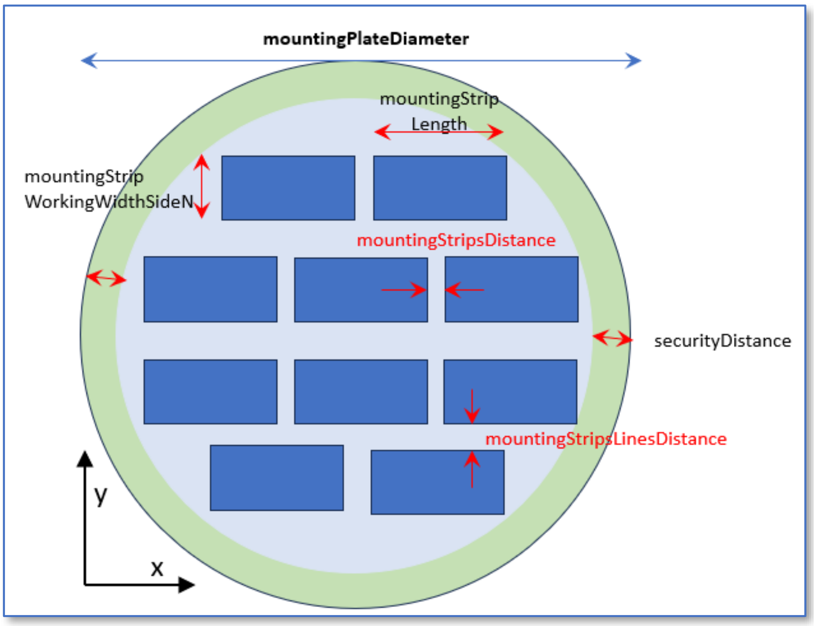


Various prism strips (green) optical contacted onto mounting strips (orange) to enable a horizontal grind and polish of one prism side.



Parameters definition needed to determine the optical contacting manufacture of a penta prism in PanDao.

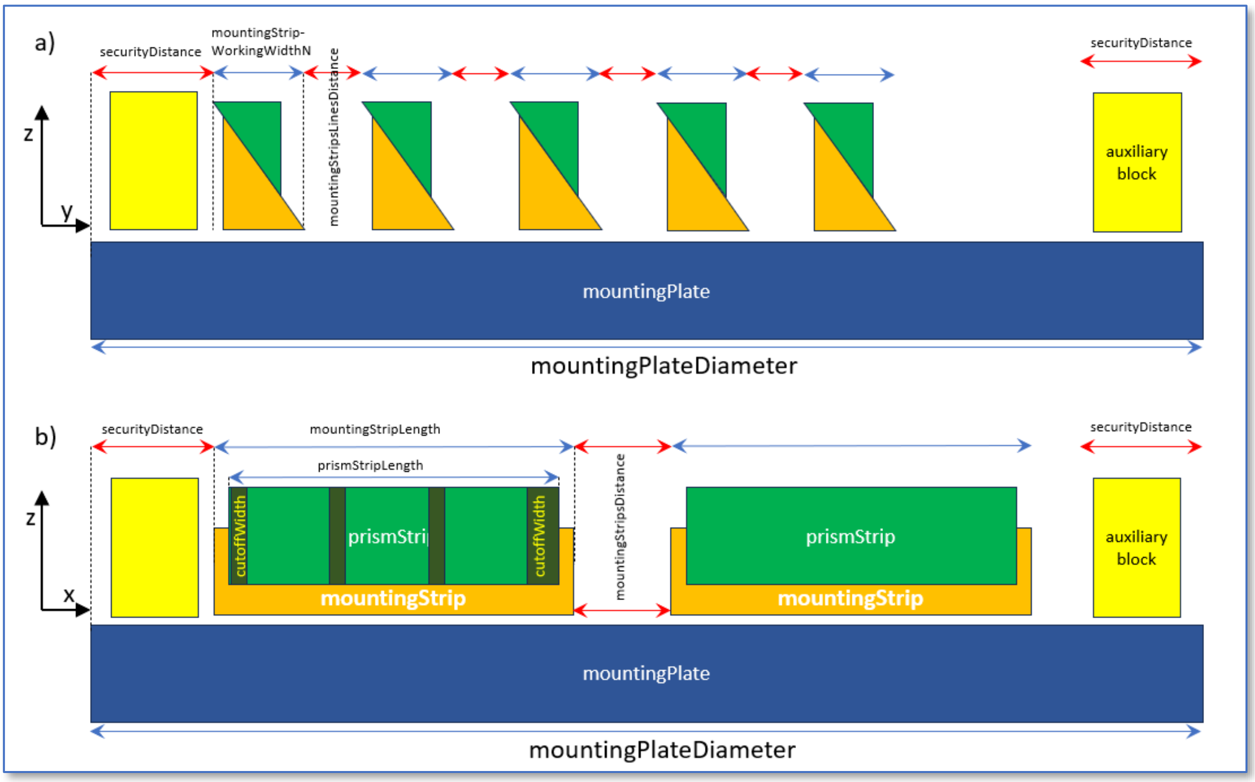
Prisms exhibit different accuracy requirements along the x-direction (along the shoulder of the prism) and within the z,y plane, which defines the ray-tracing behavior and contains the angular geometry of the prism's cross-section. For this reason, PanDao uses a block layout in the y,x plane that is linear: the prism strips are arranged in lines along the x-direction (their shoulders), with different safety distances defined in the x and y directions. PanDao determines the minimum prism strip length required by considering both the pyramidal error and the NE tolerances. The accuracy of the applied mounting plate and mounting strips, in turn, depends on the angular precision and side dimensions of the prism in the z,y plane.



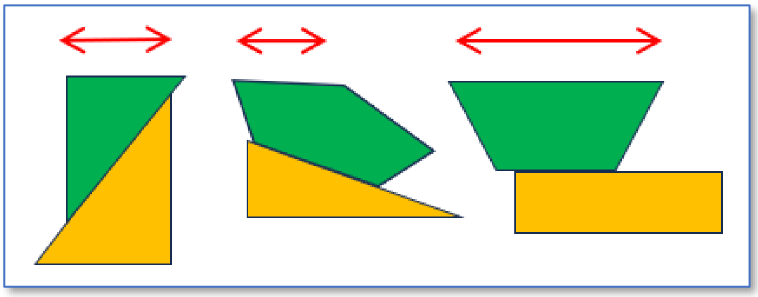
Linear block fabrication layout in PanDao with prisms shoulders along the x-axis

For each prism side, PanDao determines the appropriate geometry and accuracy of the optical contacting mounting strip, along with its required length and width.

Pandao takes ***mounting stripes cost*** into account (not selling price) and the user determines how much of it should be shared with the customer.



Example of a triangular prism strips block fabrication applying optical contacting.



Machining of a triangular prism, a penta prism and a trapez prism using mounting strips and optical contacting

PanDao displays the following specific prism output data:

- mounting regime (either mechanical mounting or optical contacting)
- mounting strip width and length

Resulting most cost-efficient fabrication chain:

Side 1:
- curve generator rough grinding
  - fabrication cost: 1.05€
  - fabrication time: 2.50min
- cnc full aperture flats grinding
  - fabrication cost: 0.98€
  - fabrication time: 2.50min
- cnc full aperture flats polishing
  - fabrication cost: 1.13€
  - fabrication time: 4.00min
  - block fabrication is used

Cost 3.16€
Time 9.00min
Capability factor: 0.997
Chain uniqueness: 9

Side 2:
- curve generator rough grinding
  - fabrication cost: 80.43€
  - fabrication time: 2.50min
  - block fabrication is used
- cnc full aperture flats grinding
  - fabrication cost: 79.97€
  - fabrication time: 2.50min
  - block fabrication is used
- cnc full aperture flats polishing
  - fabrication cost: 79.96€
  - fabrication time: 4.00min
  - block fabrication is used

Cost 240.36€
Time 9.00min
Capability factor: 0.997
Chain uniqueness: 47
Mounting strip width: 75.00mm
Used mounting regime: optical contacting

Side 3:
- curve generator rough grinding
  - fabrication cost: 9.51€
  - fabrication time: 2.50min
  - block fabrication is used
- cnc full aperture flats grinding
  - fabrication cost: 9.05€
  - fabrication time: 2.50min
  - block fabrication is used
- cnc full aperture flats polishing
  - fabrication cost: 9.04€
  - fabrication time: 4.00min
  - block fabrication is used

Cost 27.59€
Time 9.00min
Capability factor: 0.997
Chain uniqueness: 39
Mounting strip width: 75.00mm
Used mounting regime: optical contacting

Total fabrication cost: 71.03€
Serial batch lead time: 6.343156 days
Used mounting strip length: 231.900mm

Triangular prism's output: please note that the first side is generated without mounting strip (since there is not yet any backside existing); for each other side the mounting regime is displayed (either mechanical mounting or optical contacting) and the width of the mounting strip. In addition the mounting strip length is displaysd.

2x Assembly Sides:
- fabrication cost: 0€
- Surface generation during splitting

2x Assembly Sides:
- curve generator rough grinding
  - fabrication cost: 1.61€
  - block fabrication is used
- cnc full aperture flats grinding
  - fabrication cost: 1.16€
  - block fabrication is used
- cnc full aperture flats polishing
  - fabrication cost: 1.14€
  - block fabrication is used

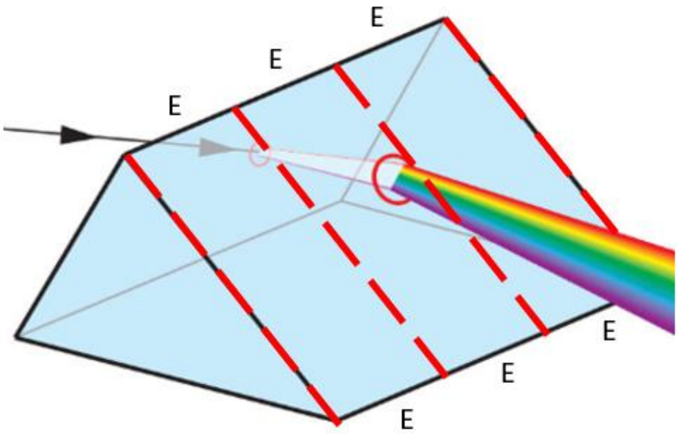
Cost 2x3.91€
Capability factor: 0.961
Chain uniqueness: 12

Assembly sides are generated by applying splitting technologies to separate the prisms out of the prism strip. Based on the required assembly side quality, two different options are applied: Either the splitting technology is "good enough" or a post processing is needed.

How is PanDao handling the splitting of prisms out of prism strips ?

Prisms are usually manufactured in a two step process:

1. the generation of the prism strip containing several prisms (in the picture below it is three prisms in one prism strip) and subsequently
2. the splitting of the prism strip into the prisms generating the their shoulder lengths E.



Prism strip cointaining three prisms as indicated by their assemblyLengths E

PanDao modells the splitting process and identifies out of many different splitting technologies (such as laser cutting, water cutting, wheel sawing, endless wire sawing, waver sawing, etc.) the optimum one for your prism.

The optimum splitting technique is being displaid in the output data generated by PanDao.

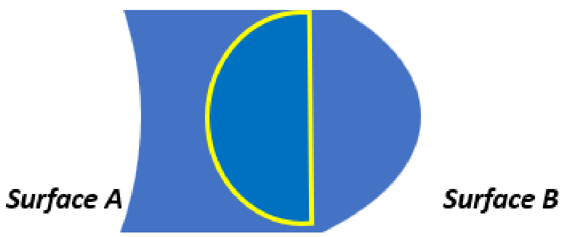
2.7. CEMENTED OPTICS

How do I manage centering tolerances of cemented optical elements?

For cemented optics (e.g. doublets, triplets or quadruplets), the centering tolerance is often specified on the technical drawing of the cemented element rather than on the drawing of its lenses.

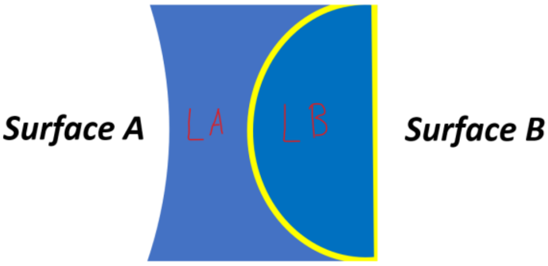
In this case, please input into PanDao the cemented element as if it would be one single lens. The two sides of this virtual lens are its outer surfaces of the cemented element (see below surface A and B of the triplet shown) and its center thickness is the sum of the center thicknesses of its individual lenses.

That way, PanDao copes with center grinding, circumference generation and multiple facets grinding of cemented optic



How do I determine cementing cost (doublets, triplets, quadruplets etc.)?

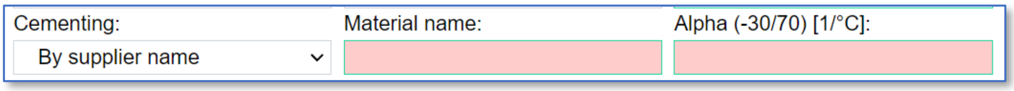
PanDao covers cementing of two optical surfaces, e.g. cementing lensB (LB) ontop of lensA (LA):

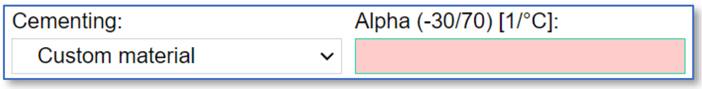


Currently, cementing is restricted to spherical and flat glass optical surfaces, only. Furthermore, PanDao considers the application of brittle, UV curing cementing materials such as e.g. Norland Optical Adhesive NOA 65.

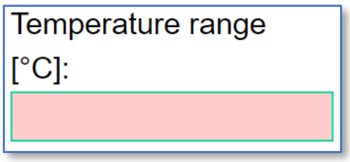
Please proceed as follows:

a) Load lensA into PanDao
b) Select the surface you want to cement the second lens (LB) onto: usually this is the side of the lens where the 4/ specifiction is defined.
c) Select the glass type of lensB to enter its coefficient of thermal expansion: “alpha” by either selecting “supplier name” (e.g. N-BK7) or by selecting “custom material”:

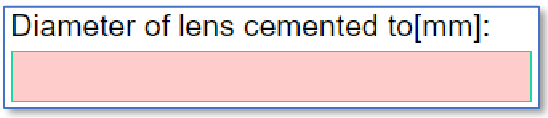




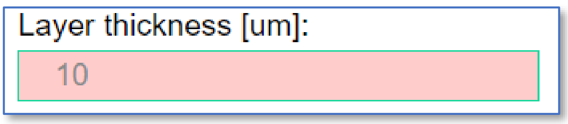
d) Enter the <u>temperature range</u> the cemented optic will be exposed to (in degrees Kelvin):



e) Enter the <u>decenter 4/</u> value of surface B to surface A of the <u>semented element</u> (please collect this value from the technical drawing of the cemented element).
f) Enter the diameter of lens cemented to the surface:



g) Enter the thickness of the layer between the two surfaces. Typically, this value is not on the drawing and only fabrication specialists can determine accurate values. If you don’t know what to enter, please enter 10um as standard value:



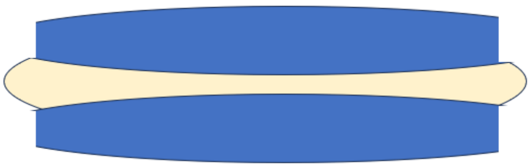
PanDao will display the best cementing technology and its cost per cemented doublet.

Please note that PanDao currently

- excludes cementing of lenses larger than 150 mm in diameter: If you require the cementing process for larger lens diameters, please contact us at info@PanDao.ch.
- covers optics cementing only for glasses, calcium fluoride, crystals, glass ceramics, chalcogenide glasses and fused silica
- allows cementing of flat and spherical surfaces.

Please respect the following delicate rules for an optimal result at minimum risk of cement cracking

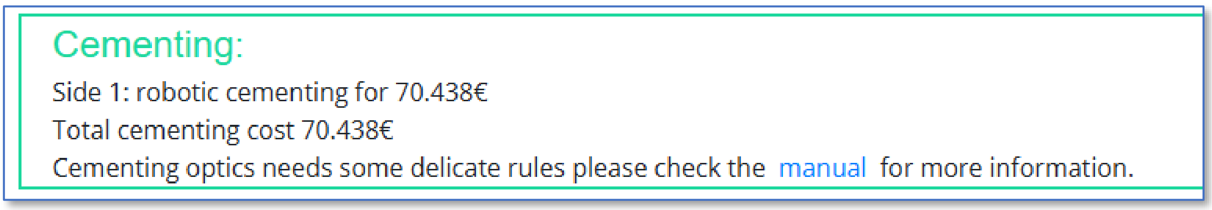
- The sides to be cemented must have the same type of shape and shape accuracy.
- A so-called plus fit must be selected, coordinated shape deviations of both surfaces within the permitted range (see 3/ of both sides), which ensure a cement gap that increases monothonically towards the outside;
- An index-matching cement is to be used and typically a 12 hour (cement dependent) rest period is to be respected after UV initiation of the cementing process;
- Cement layer thicknesses of at least 5 microns and typically not more than 10 to 20 microns lead to the best result: to guarantee this, the use of microspheres of defined refractive index can be considered; these can be positioned randomly along the crossection of the lenses (if he refractive index of the spheres matches the one of the cement) or outside of the free apertures only: The latter offering the advantage that they are ground away in the last process step during center grinding.
- The volume of cement applied should be large enough to allow a bead of cement on the outside of the optic to function as a reservoir, preventing cement cracks during curing and the associated shrinkage



Sketch of shape accuracies ratio within the allowed shape deviations (3/) and the bead of cement at the outside

How is PanDao handling the cementing of optics?

PanDao accurately models the cementing process and associated costs for any optical flat, spherical lens, or prism bonded to either flat or spherical surfaces. Based on factors such as tolerancing, geometry, dimensions, and selected lens materials, the software identifies a process window that ensures the cemented layer remains free of shear cracks. Additionally, PanDao differentiates between human and robotic cementing methods, presenting the optimal process configuration in its output data.



3. OUTPUT PARAMETERS

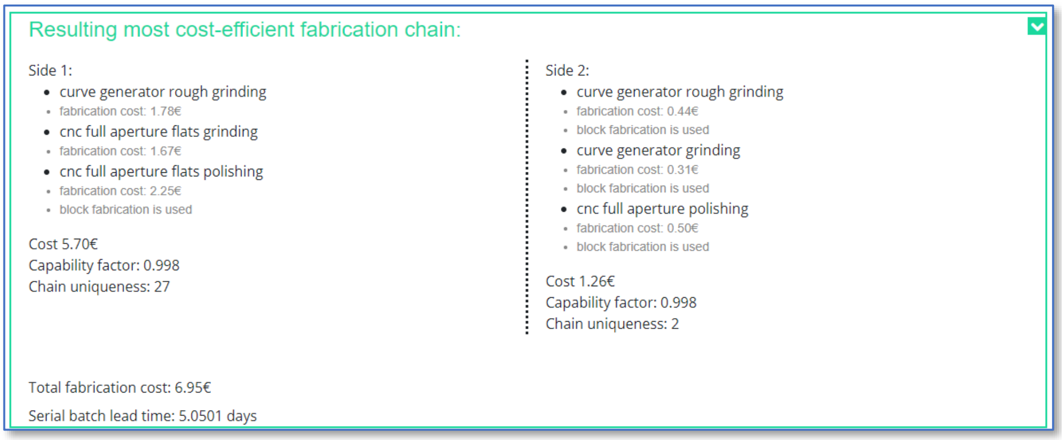
What are general boundary conditions for PanDao's output?

Tools and materials are available.

If you'll choose one of the input parameters "out of range", PanDao delivers an error message without counting this request.

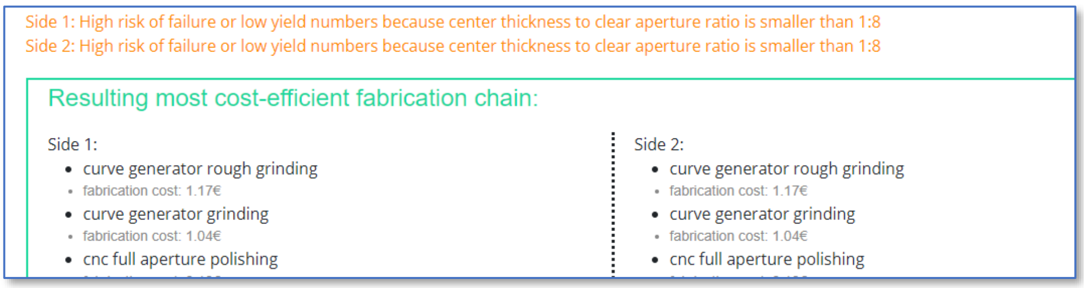
What is the output of PanDao?

PanDao determines two optimized fabrication chains: (a) the most cost-efficient and (b) the fastest fabrication chain. In addition, PanDao informs about center grinding, testing, coating and material cost needed.

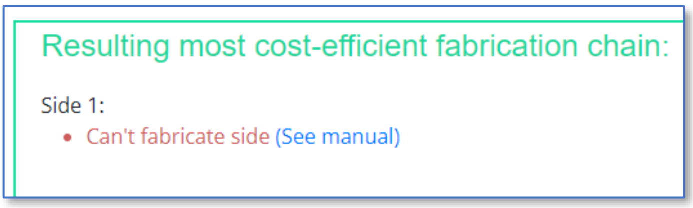


In general, there are three different possible answers given by PanDao:

h) the two optimized fabrication chains as described and shown above,
i) the two optimized fabrication chains together with a risk-alert,



j) no fabrication chain possible for the lens data inputted; in this case, PanDao delivers the message "can't fabricate":



What should I do if my lens data generates the message "can't fabricate" or if unexpected responses are displayed?

Please proceed according to the following scheme when troubleshooting:

a) double check your input data
   - Aspheres, off-axis aspheres and freeforms need a mid-spatial wavelength > 0.08 mm
   - Cockpit/Applicability: at least one of the three choices must be activated with a tick: "in industry", "RnD" and/or "university".
   - Cockpit/Level-of-Maturity: at least one of the two choices must be activated with a tick: "established" and/or "emerging technologies".
   - Double check your 4/ centering tolerance
   - General: Double check if you activated the tik for "Material suited for precision glass molding".
   - Try to enable "emerging technologies" in the cockpit/Level-of-Maturity" section.
   - Double check if you selected the desired material.

b) load a stereotype product (from the scroll-down menu at the PanDao "specify your product" input page) and convert this data step by step into your lens data.

c) contact us at info@PanDao.ch and request a PanDao DesignToFabrication service for this lens: our experts will analyze your lens data and provide a detailed manufacturability report for this lens, including suggestions on which input data should be changed or optimized.

What is Prototype Batch Lead Time (PBLT)?

Prototyping Batch Lead Time (PBLT) is the minimum time needed to produce a first batch under the following boundary conditions: (a) using one fabrication chain only (production applied sequentially and not in parallel), (b) prototyping batch orders are classified with top priority and (c) taking industrial-realistic handover times of one day per production step into account.

Prototyping lead time is an information needed for the prototyping phase and therefore being displayed only for batch sizes smaller than 50 lenses.

Prototype batch lead time: 9.00 days

What is Serial Batch Lead Time (SBLT)?

Serial Batch Lead Time (SBLT) is the minimum time needed to produce a batch in serial production under the following boundary conditions: (a) using one fabrication chain only (production applied sequentially and not in parallel), (b) taking industrial-realistic handover times per production step into account and (c) applying a batch-controlled workshop manufacturing approach.

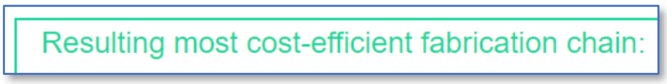
For the fastest production chain, it is assumed that the chain is optimally filled, the transfer times are minimized and the most complex production step determines the cycle rate.

Serial batch lead time: 3.9064 days

What is "most cost-effective fabrication chain"?

Based on lens' input data given, PanDao determines ***as standard output*** the best fabrication chain in terms of causing minimum fabrication cost at maximum yield; this is also called the cheapest fabrication chain.

Please note, that he most cost-effective fabrication chain is not necessarily the fastest fabrication chain.



What is the "fastest fabrication chain"?

In addition to the "most cost-effective fabrication chain", PanDao determines the "fastest fabrication chain": optimized for speed at reasonable risk while ignoring cost issues.

PanDao delivers information about both chains: the fastest and the most cost-effective: e.g. "...the "fastest chain" produces each batch 1.28 times faster than the "cheapest chain" at 2.9 times more cost.

What is "chain uniqueness"?

This output parameter helps in the risk assessment of the most cost-effective fabrication chain determined. 'Chain uniqueness' informs about how many fabrication chains exist within a fabrication cost band of 20 % above (and including) the cheapest fabrication chain.

In the example below, there are two other manufacturing chains existing that do not cost more than 20% more than the optimal manufacturing chain and use other technologies.

What is "chain capability"?

The 'chain capability' is a measure of the level at which the fabrication technologies must perform their duty in the best manufacturing chain.

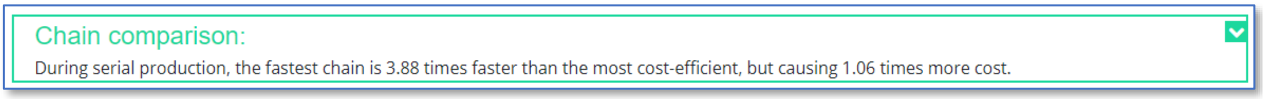
At 'chain capability' 100 %, the chain has to be applied at state-of-the-art processing level.
Below 100%, tolerancing could be further tightened (up to capability = 100%) without the need of a technology change.

The chain in the example shown below has a ‘Capability factor’ of 99.8% (Capability factor: 0.988)

What is the difference between the “most cost-effective fabrication chain” and the “fastest fabrication chain”?

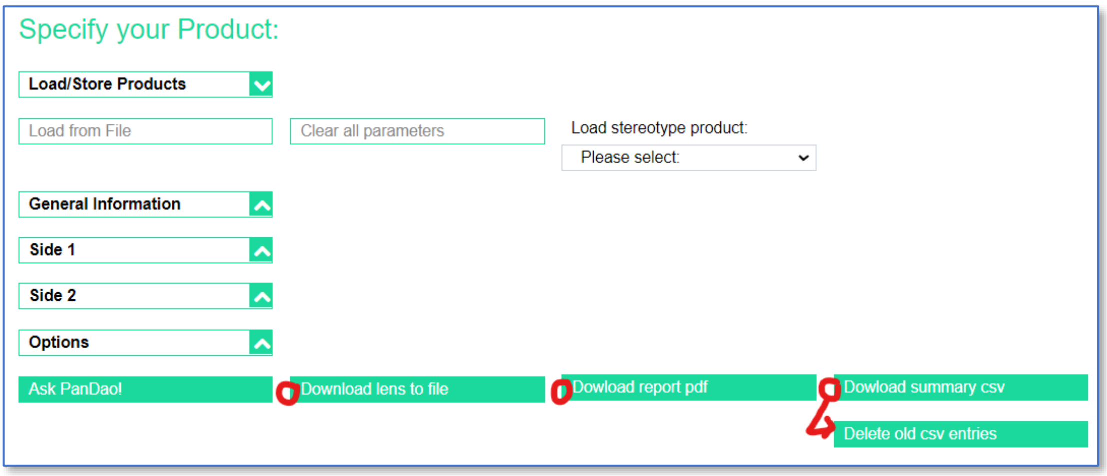
The “most cost-effective fabrication chain” is the chain with minimum fabrication cost at maximum yield; it is not necessarily the fastest chain possible.

The “fastest fabrication chain” is the fastest possible fabrication chain optimized for speed at reasonable yield while ignoring cost issues.



How can I document PanDao’s results (the PanDao Report)?

You can save lens input data any time and reload later for further analysis by PanDao or by your optical design software. You can furthermore download a full PanDao report of your lens as a pdf file or a commercial summary as an Excel file; PanDao reports can be downloaded here:



- "Download lens to file": the PanDao input data is downloaded into a json file and can be reloaded into PanDao any time.
- Download report pdf": a full report including cost and risk information as well as a management summary and literature references to all required optical fabrication technologies.
    - The PanDao report can be read-in as input
    - Please avoid Inverted commas, "", in the descrition section of the lens

PANDAO
FROM OPTICS TO FABRICATION

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Producibility report for PanDao Report:

Description:
The PanDao report summarizes all output generated by PanDao AND can be used to lre-oad the lens data again into PanDao .

Managment summary:

	Total fabrication cost [€]	Lead time [days]
cheapest chain	10.99	4.350
fastest chain	14.95	4.350

Production:
Batch size: 300
Total number of lenses: 300

Options:
Wage level: low wage companies
Technology selection: PanDaoDefault
Excluded technologies:
Applicability: In Industry
Level of maturity: Established
Enforce modling: false
Allow block fabrication: true

- "Download summary csv": download an Excel file with the cost details of your lens; You can use the "Delete old csv entries" button to write the cost information to a new Excel file: this allows you to sum up the cost informations for an entire objective into one file.

	A	B	C	D	E	F	G
1	name	most cost efficent chain cost [Euro]	fastest chain cost [Euro]	center grinding cost [Euro]	coating cost [Euro]	testing cost [Euro]	material cost [Euro]
2	PanDao Report	8.92	12.88	0.05	1.07	0.87	0.0815
3							

4. PanDao MASTER CLASS: specialities and tricks in optics fabrication

Tips and tricks for high level usage of PanDao.

4.1. General usage

The following is valid for the usage of PanDao with all three databases: “default”, “digital sister” and “digital twin”.

Technology selection: PanDaoDefault

Technology selection: CompanyOwned

Technology selection: DigitalTwin

How can I use PanDao for proposal writing for funded projects for e.g. EU or Innosuisse or DFG?

In the Cockpit section, select all "Applicability" and all "Level of Maturity" categories at rather low TRF levels (Technology Readiness Levels). Then review the PanDao results for your lens design under development. The resulting manufacturing chains may be suitable as a proof of concept for the project proposal.

Many thanks to Hansruedi Moser, who was the first person to win a huge project grant based a.o. on the submitted Pandao analysis of the field of technologies existing, identifying the noval technology opportunity.

Applicability:

- [x] In industry (TRL 7-9)
- [ ] Prototyping (TRL 4-6)
- [ ] Research (TRL 1-3)

Level of Maturity:

- [x] Established
- [x] Emerging Technology

How can I determine, if a substitute glass that is suitable for precision glass molding might enable a more cost-efficient fabrication chain?

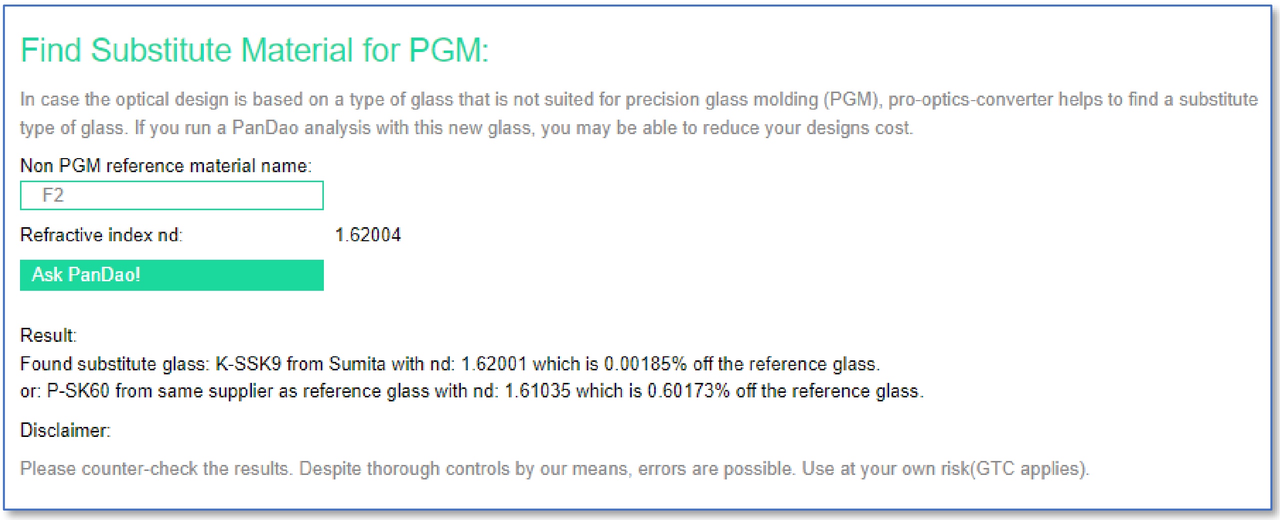
Many optical designs use mineral glasses that are not suitable for precision glass molding (pgm). In order to determine whether a redesign using a moldable pgm glass would make sense, PanDao offers a way to check in advance if (and how much more) a redesign would be cost-effective in terms of manufacturing costs.

To that aim,

1. open the PRO-OPTIC-CONVERTER and type in the glass used so far.
2. PanDao will determine out of more than six different glass manufacturers catalogues, e.g. Hoya, Sumita, Schott, Nikon, Ohara, Vitron or CDGM, a pgm substitute glass featuring a minumal difference in refractive index value.
3. Subsequently, please read your design into PanDao with the glass type substituted by the pro-optic-converter-identified pgm glass.
4. If this pgm substitute glass allows the use of pgm, enabling cheaper production, then will make sense to start redesigning the lens shape and tolerances to adapt to the substitute glass.

PRO-OPTIC -CONVERTER

Find substitute material for PGM	This tool allows you to finda substitute glass with minimum delta in refractive index and that is suitableto beprocessed with precision glas molding (pgm): for details, please consult the “PanDao Master Class” section.

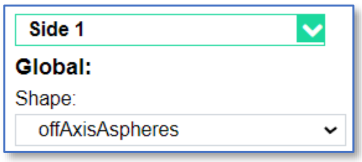


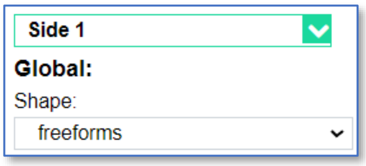
How can I select the best production strategy for an off-axis asphere?

Please note that there are two possible ways to generate off-axis aspherical optics and that the cost of both can be determined applying PanDao:

a) input of the lens as an off-axis aspherical element or
b) input of the lens as a freeform element.

Subsequently, you can choose the best variant for you taking cost and availability of technologies into account.



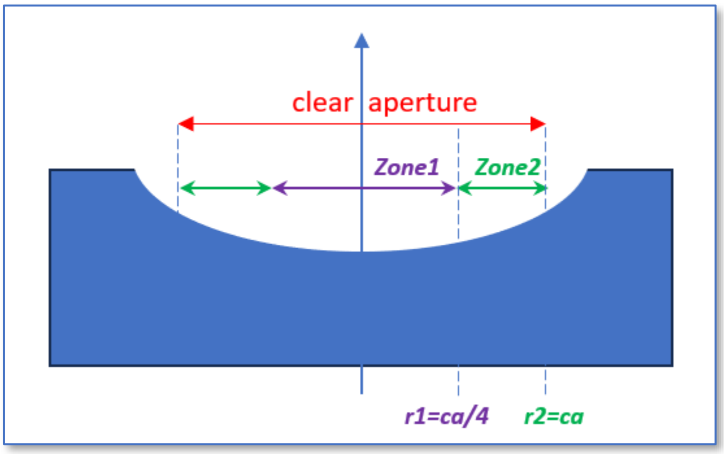


How can I apply PanDao to optics with different zonal quality levels within the clear aperture?

PanDao can be applied to determine the optimum cost, risk and fabrication chains for optics with multiple zonal quality levels (featuring e.g. different values of surface roughness or shape accuracy or midspatial wavelength or defect size). This requires a series of “ask PanDao” requests.

For example, consider a lens surface with two zonal quality levels within the clear aperture (ca):

- ***Zone1***, a central zone from the optical axis (at r = 0 mm) to r = ca/4, and
- ***Zone2***, a second zone from here to the clear aperture.



Lets assume that Zone1 has more stringent quality requirements than Zone2. In order to “pandao” (ask PanDao) this lens, the following procedure is required:

a) *Pandao* this side of the lens
    i. applying for the whole cleare aperture the Zone2 quality; use lens diamater as required: Save the result as “PanDao_A”.
b) *Pandao* this side of the lens applying for Zone1 (ca/2) the Zone2 quality; set cleare aperture lensDiameter = ca = Save the result as “PanDao_B”.
c) *Pandao* this side of the lens applying for Zone1 (ca/2) the Zone1 quality; set lensDiameter=ca. Save the result as “PanDao_C”.
d) The final PanDao result for this side of the lens = Pandao-A – PanDao_B + PanDao_C

Production of a large number of small-diameter plano parallel plates?

There are two ways to determine the production of plano parallel plates:

a) input the plano parallel plate directly into PanDao.
b) Singling out of a big plate:
    i. Input a plano parallel plate into PanDao that contains a large number of the required small-diameter plano parallel plates. In this case, you need to determine the number “n” of the smaller plano parallel plates that can be drilled out of the bigger one (taking into account the wall thickness of the grinding cup wheel to be applied).
    ii. Subsequently you will need to determine the cost of singling out the eventual small plano parallel plates you want to generate. To that aim, you the center grinding cost of the direct generation of one smaller plano parallel plate as described in paragraph “a)” above.
    iii. Finally, the cost of one small plano parallel plate equals the cost for the generation of the bigger plano parallel plate (devided by the number of small parts contained) plus the drilling cost for singling.

How do I input wedge plates into PanDao?

PanDao handles wedge plates as if they resemble a four sided prism with two optical surfaces and four assembly sides.

Select and specify in PanDao four surfaces: The two opposite, wedged surfaces are polished. The two other surfaces feature the same surface quality as the two assembly sides: ground surfaces used for assembly, only.

That way, you modelled the manufacture of a rectangular wedge plate. To check the additional cost of center grinding, input a plano parallel plate into PanDao and collect its center grinding cost.

How can I generate prisms with spherical, aspherical or freeform sides?

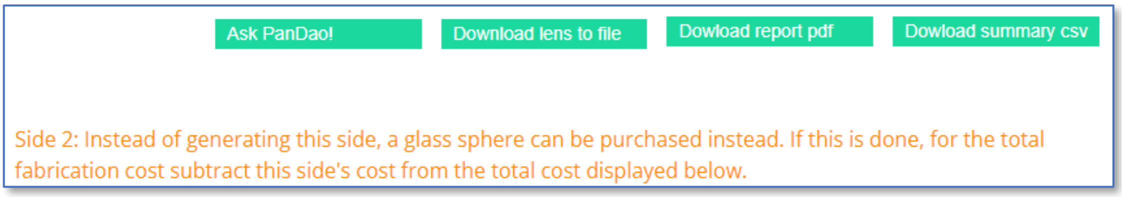
Currently, and according to the usus whidely spread in the optics industry, PanDao is not considering, that one of a prisms optical surface features a non-flat surface.

Nevertheless, PanDao can model the generation of non-flat prisms surfaces in a two step process. Lets have a look at a triangular prism with one freeform surface at side1:

1. Please generate the freeform surface as a lens featuring the freeform on one side and a flat surface on the other side; this lens features a gauge (lens thickness);
2. Please generate a triangular, flat prism, positioning side1 deeper into the prism (reducing side lengths of side2 and side3 taking the gauge of the freeform into account
3. Select side1 of the prism and apply PanDaos modelling of cementing process to determine the assembly cost of the freeform onto the prism.
4. Add all cost.

Production of a large number of small-diameter optics with a convex, spherical side?

In case the combination of order size, tolerances and properties of the lens allows it, PanDao reports that the fabrication chain of the convex, spherical surface of this lens could possibly be replaced by purchasing a glass sphere instead. In this case the opposite side of the convex side will be generated out of the purchased sphere directly:



This strategy is appropriate **if** the PanDao manufacturing cost of this convex, spherical side plus the material cost would exceed the purchase price of the glass sphere.

All other costs that PanDao calculates (e.g. coating, the manufacturing costs of the second side, testing costs, center grinding, etc.) remain in place.

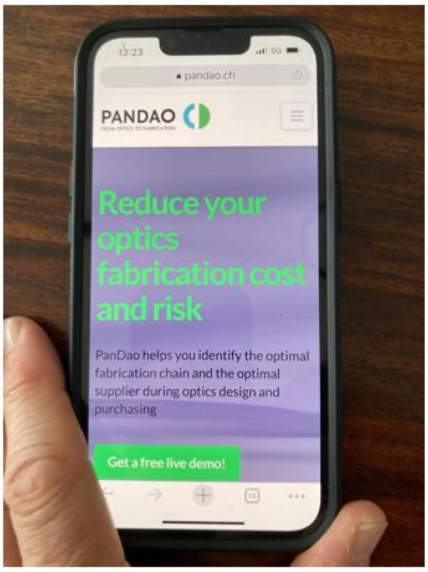
Optimization of lens specifications for minimal project risk?

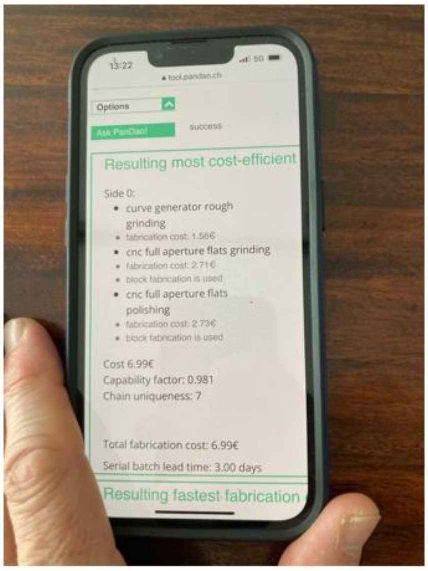
Once PanDao has determined the optimal manufacturing chain for a lens, the design can be performance stabilized at the same cost. The most performance-relevant parameters are tightened with PanDao to such an extent that this does not cause any cost increase.

lens parameter	tolerancing level required by optical designer	tolerancing level possible without any higher fabrication cost or risk
surface roughness	3 nm rms	1 nm rms
decenter	5'	1'
scratch &dig	3*0.024	3* 0.024
shape accuracy	3/5(2)	3/4/(2)

How can I use PanDao during supplier negotiations?

During negotiations, the customer and supplier can review the optimal manufacturing chain, estimate cost and required technologies. In this way, additional cost become visible if a required technology is not available, as well as the cost impact of changes in tolerances and order size. This leads to a better understanding of each other and more efficient contracts that can be relied upon...



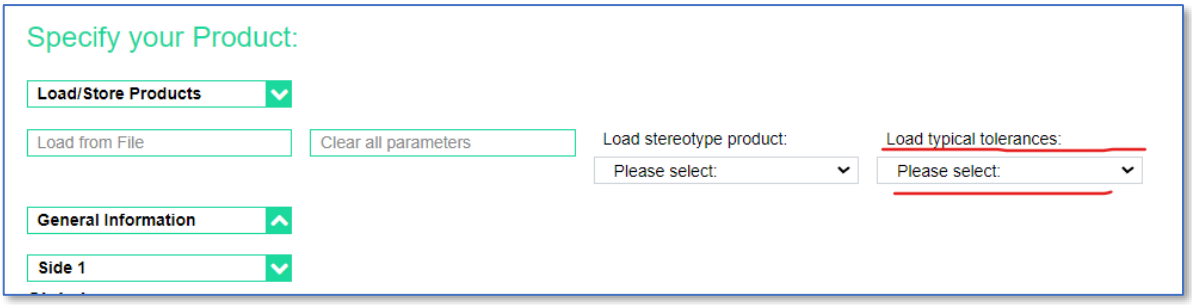


How can I check for a given lens its cost assuming tolerancing in the EUV or Visible or IR range?

PanDao offers the possibility for a given optical element which is defined by shape and geometry, coating and mechanical features (such as facets), to determine its optimum cost and fabrication chain in the folllowing application regimes **by just one click**:

1. Infrared optics quality
2. Visible – imaging optics quality
3. Visible – illuminationoptics quality and
4. EUV optics quality.

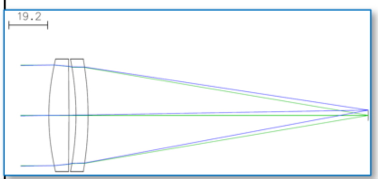
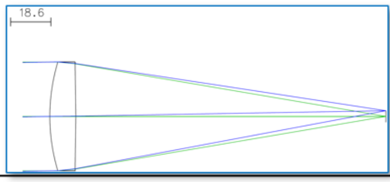
To that aim, load the lens to be tested into PanDao and apply this scroll down menue to select one of the four quality regimes listed above:



Many thanks to Nic for this brilliant idea !!

Comparison of competing optical designs?

In case two (or more) competing optical designs have been generated at similar optical performance levels, PanDao can be used to choose the one causing minimum fabrication cost (or fastest delivery times) at smallest manufacturing risk:

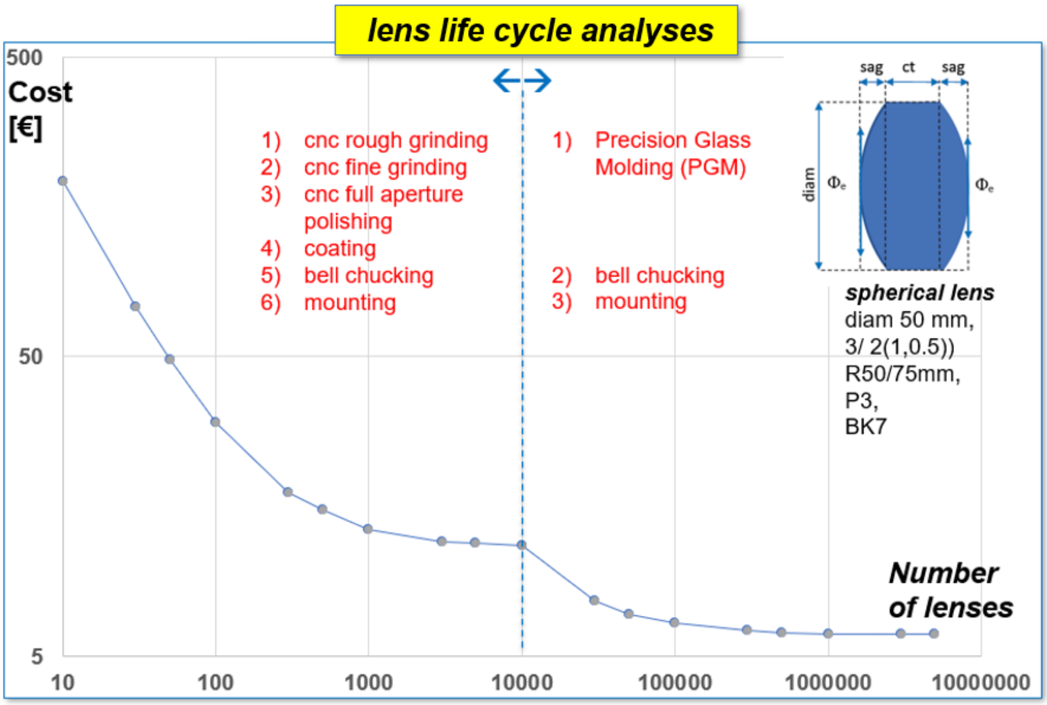
	• *focal length = 150, D = 50, NA = 0.1667, field = 5.2mm*	
design	spherical doublet, N-SF57, HK520, AR1 	aspherical lens K-PBK40, HK610, AR1 
material cost	24.2 €	4.4 €
fabrication cost	18.61 €	32.25 €

How can I carry out optics life cycle analyses?

With PanDao, the entire cost lifecycle of a lens can be determined, from prototyping through pilot series to series production. PanDao recognizes when a technology change takes place and thus enables the optimization of order sizes and negotiations with suppliers for minimum costs.

For optimum results, you might want to consider the following approach.

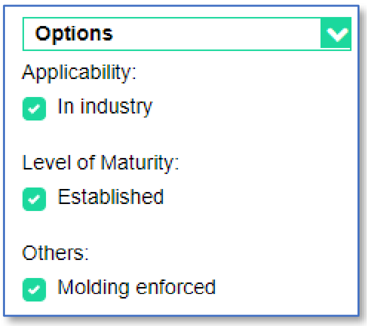
- Set up the PanDao cockpit depending on the life phases of your optics by choosing e.g. rather low TRL levels and lower yield levels for the prototyping phase.
- Apply the “download summry to csv” option to generate an Excel list of the life cycle. This enables an easy-to-handle generation of graphics and overviews such as this one:



How do I determine the cost of a possibly competing chain that applies molding?

In case the type of material is suited for molding (either precision glass molding or injection molding) and the optimal manufacturing chains displayed are not molding,

- the costs of a possibly competing manufacturing chain which uses molding (precision glass molding (pgm) or injection molding) can be determined. Please ask PanDao again but this time with the "*Enforce Molding*" field (located in the "Cockpit" section) must be switched:

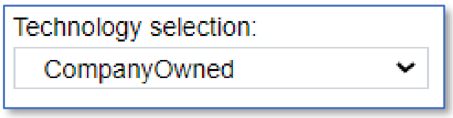


In case the type of material is not suited for molding (either precision glass molding or injection molding) and you want to find out if it makes sence to determine in optical design a substitute glass that is well suited for molding, you can ask PanDao (see picture below):

1. Change the material selection from "*by suppliers name*" to "*custom*".
2. Now you are allowed to set the tick at "*Material suited for precision glass molding*" (see picture below)
3. Then ask PanDao again with "*Enforce Molding*" field (located in the "Cockpit" section) switched on.
4. If the manufacturing situation allows molding, PanDao will display the molding chain and you will see how much money you could potentially save by making an optical design change towards a moldable type of material.

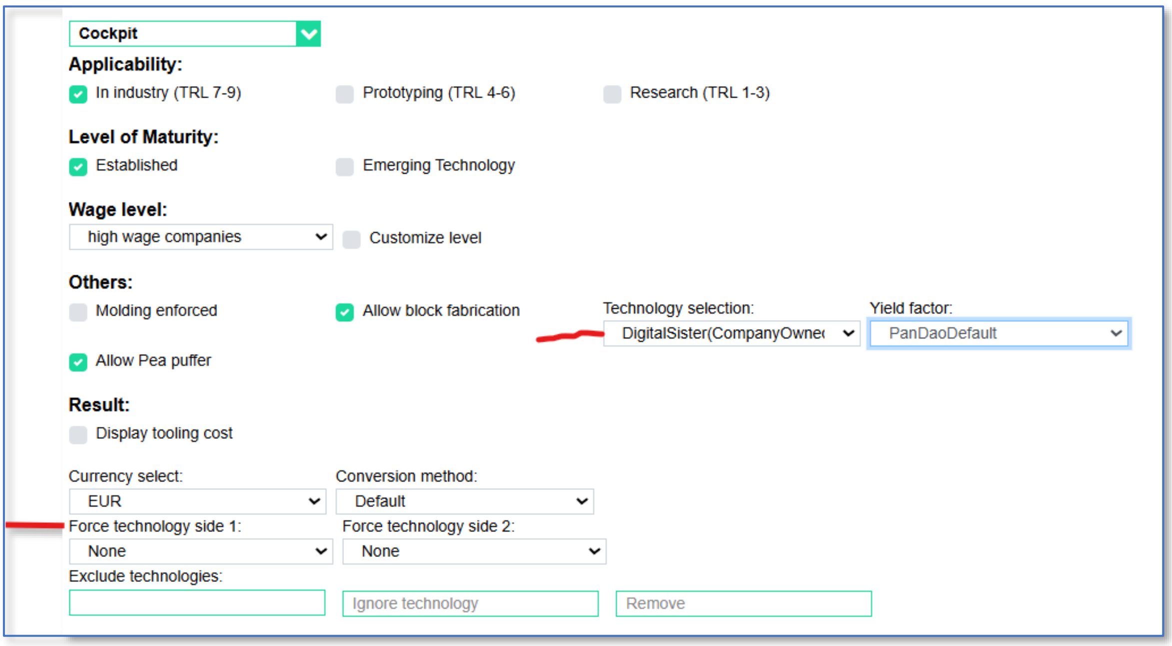
4.2. Digital sister database

The following is valid for the usage of PanDao with the “digital sister” database.



How can I determine fabrication chains which use only technologies available at my or my supplier’s company?

If the digital sister database is being chosen in the cockpit menu, PanDao determines the best fabrication chain for the limited custom list of digital sister fabrication technologies, only. These technologies are being applied at State-of-the-Art performance. In this case you can enforce a certain technology to be applied in the chain.



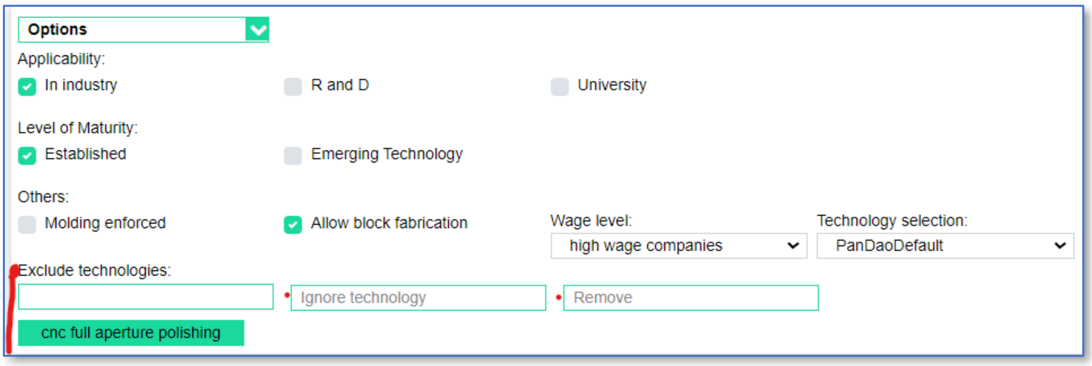
Determine the need for investment in new machineries by checking the difference between the PanDao results using "owned" and "default" databases.

The delta in fabrication cost for one lens if PanDao's default or PanDao's digital sister database is being applied can be used to determine the need for a possible investment project for buying and implementing a new technology.

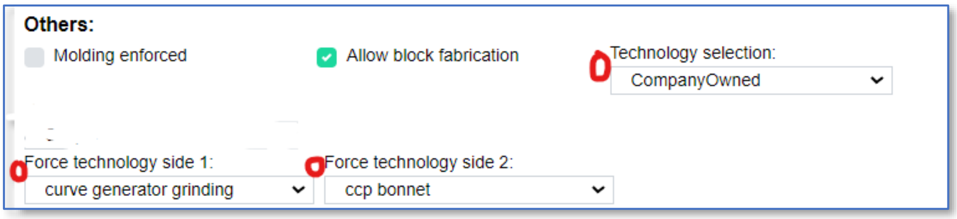
Applying capacity management

Applying the omit and the enforced cockpit it is possible to manage the capacity of technologies available at your company.

- ***Omit Technologies:*** In case one of the technologies contained in the optimal fabrication chain should be avoided: copy&paste the name into the "exclude Technology" field in the cockpit and PanDao will determine the optimal fabrication chain without using this technology



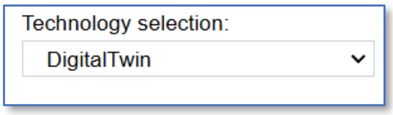
- ***Enforced OFTT:*** select the technologies from your customized list of OFTTs that PanDao should enforce to be used for finding the optimal fabrication chain.



In this way, you can steer the capacities in your production department while taking into account the resulting additional costs.

4.3. Company's digital twin

In this case, PanDao determines the best fabrication chain for the limited, customized list of company internal fabrication technologies, only. These technologies are being applied not at State-of-the-Art performance, but at the performance level defined by customer. With this option its possible to create a digital twin of the fabrication of a company.



How can I compare the performance of my machines with that of state-of-the-art machines?

Determine fabrication cost for a lens using the “digital twin” and subsequently enforce PanDao to use the same fabrication chain for this lens using the “default” database. The difference in SBLT (serial batch lead time) and fabrication cost indicates the difference in performance of your machines with state-of-the-art machinery.

How can I determine of the need for replacement investments in machinery?

The delta in cost between the results of using PanDao "digital twin" and "default" databases is a measure for the difference of performance of the machines at your company to the current state-of-the-art and can be used to determine commercially the need of starting an investment project to buy new machines.

5. PanDao's development stage

In order to ensure PanDao's state of the art level, PanDao is regularly being updated: for more details, please consult the blog section at the PanDao webpage (www.PanDao.ch) and PanDao's LinkedIn page (www.linkedin.com/company/pandao-gmbh).

PanDao		development stage
input	lens data according to ISO10110 standard and number of lenses to be produced	(a) read-in directly from your optical design software's output, (b) use a PanDao stereotype lens or (c) type in manually
	Optical design software tools that offer software interfaces to PanDao (save your lens for PanDao)	Opticstudio (Zemax), CodeV, Quadoa.
taking into account	various materials	Glasses, crystals, metals (magnetic and non magnetic), glass ceramics, ceramics, PMMA, PC, COC, SG95, UV hardening polymeres, CR39, Zeonex, binderless tungsten carbide (WC), SiC, fused silica, silicon, germanium, CaF2, Zerodur, CaF2, sapphire, ZnSe, ZinS, chalcogenide glasses
	IR materials	CaF2, BK7, Si, Ge, fused silica, sapphire, CVD_ZincSelenide_FLIR, CVD_ZincSulfide_FLIR, CVD_ZincSulfide_CLEAR, ChalcogenideGlasses
	all existing optical fabrication techniques	currently appr. 360
	processing cost	ok
	operator cost	ok
	tooling and mounting cost	ok
	uptime and downtime of machines	ok
	job setup time on the machine	ok
	company's commercial settings: bank interest and loan payback times, salaries, wage level, etc.	PanDao offers the selection of three companies wage levels for fabrication cost calculations. In addition, it is also possible to input one's individual commercial parameters
output	fabrication cost: ***360 optical fabrication technologies (OFT) are competing*** to generate the ***optimum optics fabrication chain*** for a given optical element: The most-cost efficient chain and the fastest chain	ok
	center grinding cost: ***6 center grinding technologies are competing*** to be applied as the most cost-efficient technology for a given optical element: either a single element or a cemented lens group	ok
	material cost	ok
	coating cost	ok
	testing cost	ok
	cementing cost: ***8 cementing processes handled by humans or robots are competing*** *to cement optical elements goups (e.g. doublet)*	ok
	splitting cost: ***9 splitting processes are competing*** to separate optical elements out of e.g. a waver or a prism strip	ok
	fabrication risk analysis	ok
	manufacturing chain quality assessment	ok
	cost impact analysis	ok

included	optics with any combinations of flat, spherical, cylindrical, freeform, off-axis aspherical or aspherical surfaces	ok
	maximum number of optical surfaces	two
	prisms and wedge plates	ok
	lens facet stages and protective chamfers	ok
	non-circular lens perimeter shapes	ok
	clear apertures	from 0.3 mm to 1.5 m
	surface quality	from IR to EUV optics
	order's batch size	from prototyping to mass production
optional	using technologies available at your or your supplier's company: determination of optimal optics fabrication chains, e.g. the most-cost efficient chain and the fastest chain	ok
	capacity steering tool for your workshop's technologies	ok
currently excluded	overhead cost	this strongly varies from department to department and company to company and is typically a corporate secret
	assembly cost, housing cost, acylinders, beam splitters, glass-spheres, GRIN lenses, nanomere materials, consumer glass (e.g.: bottles, windows, pipettes), mechanical components, glass fiber, lithography or on-chip optics, diffractive optics, meta-surfaces and holograms.	**not yet** included…

Included material catalogues:

Company name:	**Last updated:**	**Cost information available?**	**Comments:**
Schott	21.05.2025	yes	Alpha value at: -30 to 70°C Pricelist January 2025
Sumita	15.04.2024	no	Alpha value at: -30 to 70°C
Ohara	28.03.2025	yes	Alpha value at: -30 to 70°C
Hoya	21.04.2021	no	Alpha value at: -30 to 70°C
Nikon/Hikari	01.07.2022	no	Glasses alpha value at: -30 to 70°C FusedSilica alpha value at 25 to 100°C Hikari pricelist 2023
CDGM	01.10.2025	yes	Alpha value at: -30 to 70°C, F2 and F5 are duplicated names with materials from Schott. They are renamed to F2-CDGM and F5-CDGM.
Corning	21.07.2015	no	FusedSilica only alpha 0 to 200°C
Haraeuse	18.1.2024	no	FusedSilica alpha at 0°C from graph
Leoni	01.01.2011	no	FusedSilica only alpha 25 to 100°C
Vitron	08.06.2014	no	ChalcogenideGlasses for IR

If you use any material supplier who is not listed here or you think something is off:

- please let us know: info@pandao.ch

6. PanDao's references

Abstract Along our trail towards harmony between optics designers and optics manufacturers, PanDao carries out research, holds webinars, gives invited university lectures and publishes scientific papers together with collaboration partners around the globe.

PanDao sincerely thanks all co-authors for invaluable discussions, support and friendship: Prof. Daewook Kim, University of Arizona, USA; Prof. Jens Bliedtner, University of Jena, Germany; Prof. Irina Livshits, University of St.Petersburg, Russia; Prof. Jessica Degrote, University of Rochester, Prof. Jyrki Saarinen, University of East Finland; Finland, Mrs. Olga Resnik and Mr. Yosi Arazi, JOYA Team, Israel, Prof. David Walker and Prof. Guoyu Yu, Huddersfield University, UK; Ray Williamson, SPIE fellow, consultant, USA; and Eckhard Langenbach, senior optics designer and member ISO standard commission, Switzerland.

Since PanDao was founded in 2019

Webinars & Seminars

- 2025 October Spectaris GmbH, "KI in der Photonik, Leserfertigungstechnik und Optikdesign», Berlin, Germany
- 2025: Invited talk, "Smart Optics Factory", at the EPIC "Technology Meeting on Disruptive Optics" Seminar at Thales, France, April 2025
- 2024: EPIC "Technology Meeting on Photonics for XR: through emerging technologies and challenges", at Microsoft company, Eespo, Finnland (https://epic-assoc.com/events/epic-technology-meeting-on-photonics-for-xr-through-emerging-technologies-and-challenges-at-microsoft/)
- 2024: Optica "Freeform Optics Industry Summit", at Opimax company, Rochester, New York, USA (https://www.optica.org/events/industry_events/2024/optica_freeform_optics_industry_summit_at_optimax/)
- 2023: EPIC "Technology Meeting on Optical Design and Simulations: Tools and Use-cases", online (https://epic-assoc.com/events/epic-online-technology-meeting-on-optical-design-and-simulations-tools-and-use-cases/),
- 2023: Ansys, Optics Studio Release presentation: "Optics Studio's new feature: Export Data To PanDao", online,
- 2022: three webinars: 1) PhotonicsMedia, 2) EPIC new product release, 3) interview and Webinar with Dr. Jose Pozo (now CTO Optica (OSA))
- 2021: four webinars: 1) PhotonicsMedia, 2) BayernPhotonics, 3) Zemax Envision, 4) EPIC new product release
- Jose Pozo (CTO Optica, www.optica.org) recorded a PanDao Company Video https://www.linkedin.com/posts/josepozophotonics_stgallen-switzerland-activity-6974711562188034048-DY9y?utm_source=share&utm_medium=member_desktop

Tutorials:

- 2025 November SPIE webinar on "modelling of design to manufacture"
- 2024 September: EOSAM24 conference, Naples, Italy
- 2023 September: EOSAM23 conference, Dijon, France
- 2023 June: "Optical Design and Fabrication (ODF)" congress, Quebec City, Canada
- 2022: EOSAM22 conference, Porto, Portugal
- 2021: EOSAM21 conference, Rome, Italy

University lectures

- 2025: University of Rochester (USA),
- 2024: University of Rochester (USA), University of Arizona (USA), University of Eastern Finland, Joensu, Finlannd
- 2023: University of Tokio (Japan), University of Rochester (USA), University of Arizona (USA), University of Huddersfield (USA), EAH Fachhochschule Jena (Germany)
- 2022: University of Rochester (USA), University of Arizona (USA), University of Huddersfield (USA), EAH Fachhochschule Jena (Germany)
- 2021:University of Rochester (USA), University of Arizona (USA), University of Huddersfield (USA), EAH Fachhochschule Jena (Germany)

White Papers

[1] "Do you speak optica? Streamlining optics fabrication", Electro Optics Journal 2022 https://www.electrooptics.com/feature/do-you-speak-optica-streamlining-optics-fabrication,
[2] "Develop and apply innovative methods and tools", PhotonicsViews Journal, 18: 1-1., https://doi.org/10.1002/phvs.202170401, 2021
[3] "Optical fabrication chain design", PhotonicsViews, 18: 43-45. https://doi.org/10.1002/phvs.202100051, 2021

Books contributions

[1] **Book chapter** O. Faehnle, Irina Livshits, Jyrki Saarinen, Daewook Kim and Jens Bliedtner, " Modulation optischer Fertigungsketten?", Jahrbuch für Optik und Feinmechanik 2020, Herausgeber: Dr.-Ing. Wolf-Dieter Prenzel, ISBN978-3-00-068425-8, OPTIK-Verlag Dr. Prenzel, Gorlitz, Deutschland, 67., 2022
[2] **Book chapter** O.Faehnle, "Optikfertigungskettendesign" in Jens Bliedtner, Günter Gräfe, «Optiktechnologie», book, Hanser, ISBN 978-3-446-42466-1, 2022

Scientific Papers

[1] **Invited paper** O.Faehnle, "The smart optics factory", Optica's Optical Design and Fabrication congress (ODF), Denver, USA, June 2025
[2] T.Pickering, E.Elliott, E.Lepekhin, N.Papachristou, P.Chiu, O.Fähnle, M.Tinner, E.Langenbach, "Translating Optical Design Specifications into Manufacturing Terminology: Bridging the Gap Between Designers and Manufacturers", SPIE conference on "Precision Optics Manufacturing", Deggendorf Institute of Technology, Deggendorf, Germany, May 2025
[3] O.Faehnle, M.Balkonis, J.DeGrote Nelson et.al. "The pea puffer aspheres: circumference optimized aspheres ccp polishing", EOSAM24 conference on "Optical system design tolerancing and fabrication", European Optical Society (EOS), Napels, Italy, 2024 (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://pandao.ch/wp-content/uploads/2025/01/EOSAM24-PeaPuffer.pdf)
[4] **Invited paper** O.Faehnle, J.Bliedtner, "Simulation of Freeforms Optics Fabrication Chains in Optics Design", Optical Design and Fabrication Congress , Tucson, USA, 2024
[5] **Invited paper** F.Deurr, O.Fähnle, "Fermat meets PanDao: cost-efficient lens design", SPIE conference Optical Design and Engineering IX, Strassbough, France, **2024**
[6] **Journal paper** Walker, D., Ahuir-Torres, J.I., Akar, Y., O.Faehnle et al. "Bridging the Divide Between Iterative Optical Polishing and Automation", in the J. of Nanomanuf Metrol 6, 26 (2023), https://doi.org/10.1007/s41871-023-00197-3, 2023

[7] Fabian Duerr, O.Faehnle and Hugo Thienpont, “Starting Point Generation for Imaging Systems under Practical Constraint”, OSA’s Intenational Optical Design Conference (IODC), part of the Optical Design and Fabrication congress (ODF), Quebec City, Canada, June 2023

[8] **Invited paper**: O.Faehnle, Rolf Rascher and Marco Tinner, “Nextstep in Optics Fabrication: moving from machining to processing”, 12. Wetzlarer Herbsttagung "Moderne Optikfertigung», Wetzlar, Germany, September 2022

[9] O.Resnik, O.Faehnle and Y.Arazi, “Dynamic optimization of optical design process by means of producibility modulations”, EOSAM22 conference on “Optical system design tolerancing an fabrication“, European Optical Society (EOS), Porto, Portugal, September 2022

[10] **Invited paper**: O.Fähnle and I.Livshits, “Modeling of Optical Fabrication Chains during Optics Design”, International Conference on Optics-photonics Design & Fabrication (ODF), JSAP (The Japan Society of Applied Physics), Sapporo, Japan , August 2022

[11] M.Tinner, I.Livshits and O.Faehnle, " Producibility analyses during the optical design stage", DGaO Tagung, Bremen, Germany 2021.

[12] O.Faehnle and I.Livshits, “Optical Fabrication Chain Modeling”, SPIE conference on “Optical System Design”, Madrid, Spain, 2021

[13] O.Faehnle, Develop and apply innovative methods and tools. PhotonicsViews, 18: 1-1. https://doi.org/10.1002/phvs.202170401, 2021

[14] O.Fähnle, Rascher, R. and Tinner, M., Optical fabrication chain design. PhotonicsViews, 18: 43-45. https://doi.org/10.1002/phvs.202100051, 2021

[15] O.Faehnle and I.Livshits, “Manufacturing risk management in optical design”, EOSAM20 conference on “Optical system design tolerancing an fabrication“, European Optical Society (EOS), Rome, Italy, September 2021

[16] O.Faehnle, J.Bliedtner and I.Livshits, “GLASTICS: decision making in the optical design regime where designs made of GLASS compete with those made of PLASTICS”, EOSAM20 conference on “Optical system design tolerancing an fabrication“, European Optical Society (EOS), Rome, Italy, September 2021

[17] I.Livshits, A.Petukhov, J.Saarinen, O.Faehnle, “Supervised Machine Learning in Relation to the Simplest Classification of Optical Systems”, “Optical Design and Fabrication” conference, Taiwan 2021

[18] **Invited paper**: O.Fähnle and I.Livshits, “Optical Fabrication Process Modeling”, OSA’s Optical Fabrication and Testing conference (OF&T), part of the Optical Design and Fabrication congress (ODF), Rode Island, NY, USA , June 2021

[19] O.Faehnle, E.Langenbach and I. Livshits, “Balancing optical system design and optical fabrication chain design”, SPIE conference on “Precision Optics Manufacturing”, Deggendorf Institute of Technology, Deggendorf, Germany, April 2021

[20] Fähnle, O., Rascher, R. and Tinner, M. (2021), Optical fabrication chain design. PhotonicsViews, 18: 43-45. https://doi.org/10.1002/phvs.202100051 2021

[21] **Journal paper:** I.Livshits, T.Tochilina, O.Faehnle and S.Volkova, “Design strategy and management of aberration correction process for lens with high complexity index”, Scientific and Technical Journal of Information Technologies, Mechanics and Optics, 2021, vol. 21, no. 1, pp. 40–51 (in Russian). doi: 10.17586/2226-1494-2021-21-1-40-51, 2021

[22] **Journal paper:** I.Livshits and O.Faehnle, “Producibility analysis of a lens system during the optical design stage”, Scientific and Technical Journal of Information Technologies, Mechanics and Optics, ISSN 2226-1494 (print), ISSN 2500-0373 (online), St. Petersburg, Russia, doi: 10.17586/2226-1494-2020-20-5-625-633, No.5 2020

[23] M.Tinner, O.Faehnle and I.Livshits, “PanDao fabrication cost impact analysis software tool for optical designers”, EOSAM20 conference on “Optical system design tolerancing an fabrication“, European Optical Society (EOS), due to CoronaVirus: “proceedings only”, https://doi.org/10.1051/epjconf/202023803014, September 2020

[24] O.Faehnle, M.Doetz, C.Vogt and E.Langenbach, “Three wagons method: metamorphosis from machining to processing in optics fabrication”, EOSAM18 conference on “Optical system design tolerancing an fabrication“, European Optical Society (EOS), Delft, The Netherlands, October 2018

[25] **Journal paper:** Oliver Faehnle, “Process optimization in optical fabrication”, SPIE Journal on Optical Engineering 0001;55(3):035106. doi:10.1117/1.OE.55.3.035106., 2016

For frequently updates on PanDao’s activities and updates:

- read our blog entries: https://pandao.ch/blog/
- watch our YouTube channel: https://www.youtube.com/channel/UC318X9TJZWs2xeTjzeE40zg
- follow PanDao at ***Linkedin***: https://ch.linkedin.com/company/pandao-gmbh
- contact us at info@PanDao.ch